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MARINE EMISSION INVENTORY STUDY: EASTERN CANADA AND GREAT LAKES

Prepared for
Transportation Development Centre
of
Transport Canada

by
Levelton Consultants Ltd.
Maritime Innovation
Dr. J. Corbett

March 2006

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Engineering Solutions

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by
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in association with
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Dr. J. Corbett

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

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16. Abstract

A regional emission inventory was prepared for commercial ocean-going marine vessels operating on the Great Lakes, the St. Lawrence Seaway, and the East Coast of Canada in 2002. The main tasks completed in this project were:

1. Development of a detailed inventory of emissions of air contaminants and carbon dioxide by mode of operation using activity-based information from the Canadian Coast Guard INNAV database, together with an emission calculation tool developed using Access™ database software.
2. Preparation of a baseline emission forecast for 2010 and 2020, allowing for growth in vessel traffic and changes in engine technology and the sulphur content of domestic marine diesel oil.
3. Preparation of an emission forecast for SOx and particulate matter in 2010 and 2020 that incorporates the emission reductions that could potentially occur by implementation of a Sulphur Emission Control Area (SECA) under Annex VI of MARPOL 73/78 of the International Maritime Organization.
4. Spatial resolution of the emission inventory to regional polygons and then to 4 km by 4 km grid cells for use in regional air quality modeling studies.

Emissions are forecast to increase 9% to 13% by 2010 and 20% to 29% by 2020, as compared to emissions in 2002. Bulk carrier, container and tanker vessels were consistently the three largest contributors to emissions of carbon dioxide and the primary pollutants of concern in regard to effects on air quality. Taken together, these vessel classes contribute 67% to 74% of total emissions.

The implementation of a SECA in the study area is forecast to reduce SOx emissions relative to the level in 2002, declining 33% by 2010, and 24% by 2020. By reducing the formation of sulphate from combustion of sulphur in marine fuels, a SECA will also reduce the growth in annual PM10 and PM2.5 emissions from 13% to -5% by 2010 and from 29% to 8% by 2020.

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16. Résumé

Le projet a consisté à réaliser un inventaire régional des émissions produites par les navires marchands transocéaniques naviguant sur les Grands Lacs, dans la Voie maritime du Saint-Laurent et sur la côte Est du Canada en 2002. Voici un résumé des tâches exécutées dans le cadre de ce projet :

1. Constitution d'un inventaire détaillé des émissions de polluants atmosphériques et de dioxyde de carbone des navires selon leur mode d'exploitation, à l'aide d'un outil de calcul des émissions développé au moyen du logiciel de base de données Access™, appliqué aux données sur l'activité des navires contenues dans le système INNAV de la Garde côtière canadienne.
2. Établissement de prévisions de base concernant les niveaux d'émissions pour 2010 et 2020, en admettant une croissance du trafic maritime et des changements dans la technologie des moteurs et dans la teneur en soufre du mazout marin canadien.
3. Établissement de prévisions concernant les niveaux d'émissions de SO_x et de particules pour 2010 et 2020, en admettant les réductions d'émissions susceptibles de découler de la désignation d'une «zone de contrôle des émissions de soufre» (ou SECA, pour *Sulphur Emission Control Area*) en vertu de l'annexe VI de la convention MARPOL 73/78 de l'Organisation maritime internationale.
4. Décomposition de l'inventaire des émissions en polygones régionaux, puis en cellules de 4 km sur 4 km, aux fins d'études de modélisation de la qualité de l'air par région.

Il est prévu que les émissions augmenteront de 9 % à 13 % en 2010 et de 20 % à 29 % en 2020, par rapport aux émissions de 2002. Les vraquiers, les porte-conteneurs et les citernes sont les trois types de navires qui contribuent le plus aux émissions de dioxyde de carbone et des principaux polluants responsables de la dégradation de la qualité de l'air. Ensemble, ces types de navires comptent pour 67 % à 74 % de toutes les émissions.

La désignation d'une SECA dans le secteur étudié devrait entraîner une réduction des émissions de SO_x de 33 % en 2010, et de 24 % en 2020, par rapport à 2002. Elle devrait également réduire les niveaux de sulfates produits par la combustion du soufre présent dans les carburants marins, et contrer la croissance des émissions annuelles de MP_{10} et de $MP_{2,5}$, la faisant passer de 13 % à -5 % en 2010, et de 29 % à 8 % en 2020.

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Gaz d'échappement des navires, NO_x, CO, SO_x, MP, matières particulaires, COV, composés organiques volatils, SECA, zone de contrôle des émissions de soufre, prévision des émissions	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires imprimés. Disponible également en ligne à www.tc.gc.ca/cdt/menu.htm

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EXECUTIVE SUMMARY

A regional emission inventory was prepared for commercial marine vessels operating on the Great Lakes, the St. Lawrence Seaway, and the East Coast of Canada (Figure S-1) in 2002. Work on this project was guided by a steering committee consisting of staff from Transport Canada and Environment Canada.

The principal tasks completed in this project were:

1. Development of a spatially resolved inventory of emissions of air contaminants[1] and carbon dioxide from ocean-going commercial marine vessels in 2002 using activity-based information recorded in the Canadian Coast Guard INNAV database and an emission calculation tool.
2. Preparation of an emission forecast for 2010 and 2020.
3. Preparation of an emission forecast for SOx and particulate matter in 2010 and 2020 that incorporates the emission reductions that could potentially occur by implementation of a Sulphur Emission Control Area under Annex VI of MARPOL 73/78 of the International Maritime Organization.
4. Preparation of an emission inventory spatially resolved to regional polygons (Figure S-1) and to 4 km by 4 km grid cells.

Emissions from vessels while underway arise from the propulsion (main) engines and to a lesser extent from auxiliary engines that generate electrical power for ship services. Emissions from vessels in port arise from the main and auxiliary engines while the vessel manoeuvers to berth or anchor, and from the auxiliary engines while at anchor or at berth.

Emissions from marine vessels were calculated using the current best practice, which involves multiplying an emission factor appropriate to the combination of engine and fuel used, and the mode of vessel operation, by the estimated output energy of the propulsion (main) engine and auxiliary engines. The output energy from each engine system was calculated as the product of the engine output capacity, the in-service load factor for the engine system and the duration of operation. This calculation method is the accepted approach for individual ocean-going vessels as well as for groups of other types of smaller vessels, as long as the power, emission factor, load factor and time in mode are chosen appropriately. The challenge in such calculations is to determine the input data that reliably simulates emissions for the diverse characteristics of main and auxiliary power systems and the inherent variability of vessel movement and energy use.

The primary source of data for the emission inventory was the Coast Guard's INNAV data base for the period from June 1 2002 to May 31 2003. This data base includes the date of the start and end of individual movements of all classes of commercial marine vessels operating in Canadian waters and incorporates data on the characteristics of each vessel. The emission inventory focuses on commercial ocean-going ships with a gross tonnage of 400, or greater.

The 2003-2003 INNAV database includes data for a total of 1,789 vessels with a gross tonnage of over 400, which recorded a total of 29,603 vessel movements. Because merchant ferry movements were found to be under-reported in this database, movement records for ferries were scaled to agree with the 47,866 ferry movements estimated by Environment Canada to have

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[1] Nitrogen oxides (NOx), sulphur oxides (SOx), hydrocarbons (HC), volatile organic compounds (VOC), carbon monoxide (CO) and particulate matter (total (TPM), and size fractions less than or equality to 10 microns (PM_{10}) and 2.5 microns ($PM_{2.5}$).

taken place in 2005. This estimate is based on ferry schedules and information from ferry operators.

A key input for calculating underway emissions is the time in transit, which was estimated for each vessel by dividing the port-to-port travel distance in Canadian waters by the estimated in-service speed for the class of vessel. Analysis was conducted to determine the number of vessel movements between port areas, and to develop from this an appropriate technique for estimating transit distances. Movements between domestic ports and between domestic and international ports were considered in this analysis in two separate groups. The vessel movements between port areas were used to rank the port-to-port routes by activity level and determine the number of port-to-port routes that would need to be included to yield different cumulative percentages of total vessel activity. For domestic vessel movements, 50% of vessel movements occur between 49 ports areas and 80% occur between 451 port areas. For arrivals from foreign ports, 50% of all vessel movements are to 25 Canadian ports and 80% are to 104 Canadian ports. Based on this analysis, port-to-port transit distances were determined for all routes that comprised 80% of the total vessel movements for domestic and international trips. For each of these routes, the percentages of the distance located within regions 5 through 20 were also determined so they could be used in the spatial analysis. The most common entry and exit points were identified along the 200 mile EEZ (Exclusive Economic Zone) limit and the Canada/USA border in the Great Lakes.

The remaining 20% of the vessel trips not estimated specifically by the above method account for approximately 4,000 port-to-port routes. Simplified techniques were applied to estimate distances for these remaining routes drawing first on the pool of transit distances estimated for the most frequent 80% of trips and next by approximate distances from the centroid of one emission region to another.

The emission inventory was prepared using an enhanced version of the marine vessel emission inventory tool and data system developed for Environment Canada in 2005. This application was developed in Microsoft Access™ to generate emission estimates using a bottom-up methodology based on Lloyd's port-to-port activity data for vessels operating in Canadian waters. This application was modified to utilize the INNAV data and port identifiers, and to:

- calculate upper and lower estimates of emissions based on estimates of uncertainty in the emission factors and the vessel activity data.
- incorporate updated and revised emission factors and assumptions used to estimate engine energy output and duration of operation.
- calculate gridded (4 km x 4 km) emission results for each emission region using spatial proration tables developed by Dr. Corbett and Dr. Wang at the University of Delaware and with an output format suitable for input to regional air quality dispersion models.

A baseline emission forecast was developed that incorporated growth in the tonnage of commodities transported by ship, gradual replacement of engines in the fleet with new engines meeting the IMO NOx emission limit, and implementation of a 500 ppm sulphur content limit for marine diesel fuel sold in Canada starting in 2007.

Growth factors were developed to approximate the change in emissions by 2010 and 2020 for each vessel type relative to emissions in 2002. The surrogate used for growth in emissions is tonnage of commodities transported by each type of vessel. Growth factors were developed using national data provided by Transport Canada on the tonnage of commodities shipped in 2002 by type of vessel, and the tonnes per year of each commodity forecast to be shipped through Canadian ports in 2010 and 2020. The existing forecast anticipates that the tonnage of all categories of domestic and international commodity shipments will grow 11% (1.3% per year)

by 2010 and 21% (1.1% per year) by 2020. Containerized shipments are forecast to grow most rapidly, with growth factors of 1.29 in 2010 and 1.74 in 2020, relative to 2002. The actual overall growth rate is anticipated to be higher than suggested by the current forecast based on limited data on the historical growth trends for the Port of Montreal and US ports.

The effect of gradual replacement of existing engines in the fleet with new engines meeting the current IMO NOx emission limit for ocean-going vessels was estimated using a simple model for replacement of this equipment. Existing main and auxiliary engines were assumed to be retired at an average rate of 2% per year and replaced by new engines meeting the IMO NOx emission limits. The proportion of slow speed and medium speed engines used for main engines (95% slow speed and 5% medium speed) and the proportion of auxiliary engines using intermediate fuel oil and marine diesel oil (75% residual oil and 25% marine diesel oil) were assumed to remain constant at the values assumed for the base year. At the assumed replacement rate and with continuation of the current IMO NOx emission limit to 2020, the average NOx emission factor for the fleet is forecast to decrease 5.7% for main engines and 8.3% for auxiliary engines.

Emissions were estimated for a proposed Sulphur Emission Control Area (SECA) extending over the study area. With implementation of a SECA, all heavy fuel oil used by ocean-going vessels is required to have a sulphur content of 1.5% or less. The sulphur content of marine diesel fuel was assumed to remain unchanged from the baseline forecast. The forecast changes in NOx emissions and the percentage of heavy fuel oil and marine diesel oil used in auxiliary engines were assumed to remain the same as in the baseline forecast. The reduction in the sulphur content of heavy fuel oils from 2.7% to 1.5% for international supplies and from 1.7% to 1.5% for domestic supplies will reduce emissions of particulate matter (as sulphate) as well as SOx from main and auxiliary engines. The percentage reduction in baseline particulate matter and SOx emissions was estimated from published literature and applied to each type of vessel included in the inventory with adjustments for the initial sulphur content of the fuels used.

Table S-1 summarizes the baseline emission results for 2002, 2010 and 2020. Emissions are forecast to increase 9% to 13% by 2010 and 20% to 29% by 2020, as compared to the 2002 base year (see Table S-2). As shown in Figure S-2, bulk carrier, container and tanker vessels were consistently the three largest contributors to emissions of carbon dioxide and the primary pollutants of concern in regard to effects on air quality in the base year. The combined contribution from this group of vessels ranges from 67% to 74% of the total.

From the analysis of the emissions by month, emissions are lowest in January through March and remain near their highest levels in May, July, August, September and October. The months when minimum or maximum values occur are not the same for all pollutants.

The implementation of a SECA in the study area is forecast to decrease annual SOx emissions 33% by 2010, and 24% by 2020, relative to emissions in 2002. By reducing the formation of sulphate from combustion of sulphur in marine fuels, a SECA will also reduce the growth in annual PM_{10} and $PM_{2.5}$ emissions from 13% to -5% by 2010, and from 29% to 8% by 2020.

Table S- 1 Base Year and Forecast Emissions

Substance	Emissions				
	2002	2010		2020	
	(tonnes/year)	(tonnes/year)	% Increase	(tonnes/year)	% Increase
CO_2	3,298,991.8	3,696,368.7	12.0%	4,167,118.0	26.3%
NOx	93,699.5	102,334.5	9.2%	112,209.6	19.8%
SO_2	47,459.0	53,576.4	12.9%	61,143.3	28.8%
VOC	2,843.2	3,210.0	12.9%	3,644.2	28.2%
HC	2,843.2	3,210.0	12.9%	3,644.2	28.2%
CO	3,092.9	3,432.1	11.0%	3,834.5	24.0%
TPM	10,348.4	11,729.0	13.3%	13,362.4	29.1%
PM_{10}	8,157.0	9,241.0	13.3%	10,523.5	29.0%
$PM_{2.5}$	6,854.8	7,761.8	13.2%	8,834.9	28.9%

Table S- 2 Forecast Emissions with Implementation of a Sulphur Emission Control Area

Substance	Emissions				
	2002	2010		2020	
	(tonnes/year)	(tonnes/year)	% Change	(tonnes/year)	% Change
CO_2	3,298,991.8	3,696,368.7	12.0%	4,167,118.0	26.3%
NOx	93,699.5	102,284.4	9.2%	112,209.6	19.8%
SO_2	47,459.0	31,842.1	-32.9%	36,214.6	-23.7%
VOC	2,843.2	3,210.0	12.9%	3,644.2	28.2%
HC	2,843.2	3,210.0	12.9%	3,644.2	28.2%
CO	3,092.9	3,432.1	11.0%	3,834.5	24.0%
TPM	10,348.4	9,835.3	-5.0%	11,194.9	8.2%
PM_{10}	8,157.0	7,752.0	-5.0%	8,819.6	8.1%
$PM_{2.5}$	6,854.8	6,513.6	-5.0%	7,406.9	8.1%

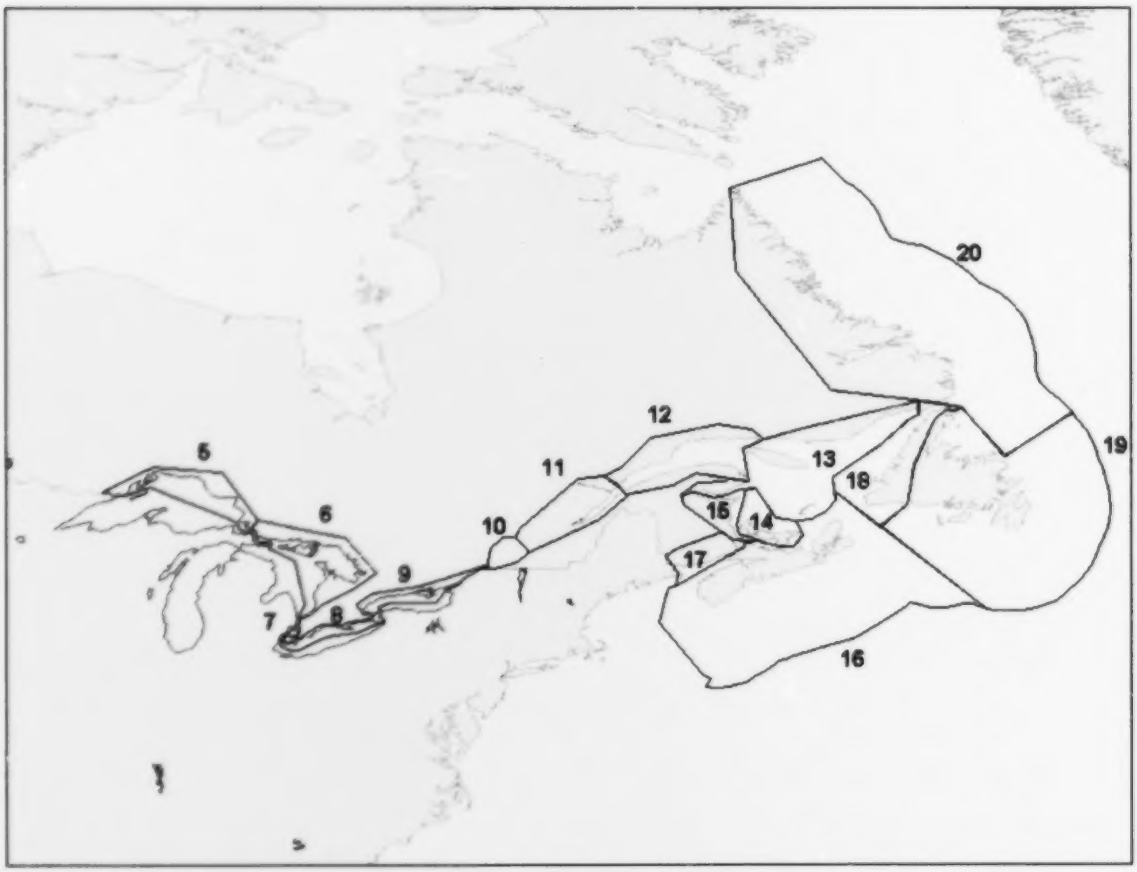

Figure S- 1 **Map of the Emission Inventory Area and the Sub-Regions used to Spatially Resolve the Emission Inventory**

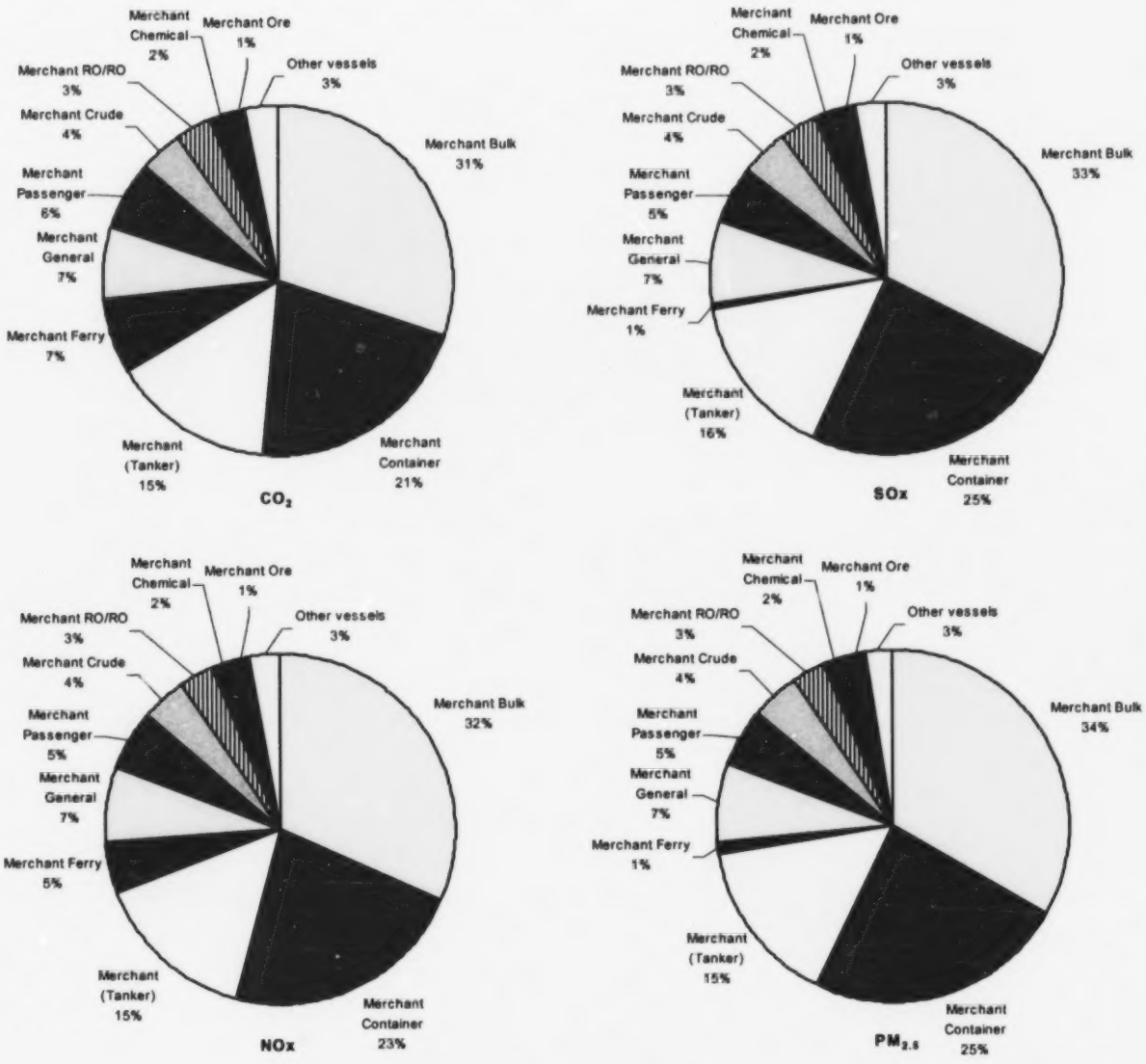

Figure S- 2 Distribution of 2002 CO_2, SOx, NOx and $PM_{2.5}$ Emissions by Class of Vessel

SOMMAIRE

Le projet a consisté à réaliser un inventaire régional des émissions produites par les navires marchands naviguant sur les Grands Lacs, dans la Voie maritime du Saint-Laurent et sur la côte Est du Canada en 2002 (figure S-1). Ces travaux ont été supervisés par un comité de direction constitué de représentants de Transports Canada et d'Environnement Canada.

Voici un résumé des tâches exécutées dans le cadre de ce projet :

1. Constitution d'un inventaire spatial des émissions de polluants atmosphériques[2] et de dioxyde de carbone produites par des navires marchands transocéaniques en 2002, à l'aide d'un outil de calcul des émissions appliqué aux données sur l'activité des navires contenues dans le système INNAV de la Garde côtière canadienne.

2. Établissement de prévisions des niveaux d'émissions pour 2010 et 2020.

3. Établissement de prévisions concernant les niveaux d'émissions de SO_x et de particules pour 2010 et 2020, en admettant les réductions d'émissions susceptibles de découler de la désignation d'une «zone de contrôle des émissions de soufre» (ou SECA, pour *Sulphur Emission Control Area*) en vertu de l'annexe VI de la convention MARPOL 73/78 de l'Organisation maritime internationale.

4. Décomposition de l'inventaire des émissions en polygones régionaux (figure S-1) et en cellules de 4 km sur 4 km.

Les émissions des navires qui font route proviennent des machines (principales) de propulsion et, dans une moindre mesure, des machines auxiliaires qui produisent l'électricité pour le service de bord. Les émissions des navires dans un port proviennent des machines principales et auxiliaires lorsque celui-ci manoeuvre vers un poste d'amarrage ou un mouillage, et des machines auxiliaires lorsqu'il est immobilisé à un mouillage ou amarré.

Les émissions des navires ont été calculées à l'aide de la meilleure pratique actuellement reconnue, qui consiste à multiplier la quantité d'énergie produite par les machines (principales) de propulsion et les machines auxiliaires par un coefficient d'émission correspondant à la combinaison moteur/combustible utilisée et au mode d'exploitation du navire. Pour calculer l'énergie produite par chaque moteur, on a multiplié la puissance du moteur par son facteur de charge en service et sa durée de marche. Cette méthode de calcul est acceptée aussi bien pour des navires transocéaniques individuels que pour des ensembles de navires d'autres types et plus petits, pour autant que la puissance, le coefficient d'émission, le facteur de charge et la durée de marche dans un mode d'exploitation soient judicieusement choisis. La valeur de tels calculs repose sur la détermination de données d'entrée qui mènent à des simulations fiables des émissions, compte tenu des diverses caractéristiques des machines principales et auxiliaires, et de la variabilité intrinsèque des mouvements des navires et de leur consommation d'énergie.

La base de données du système INNAV de la Garde côtière canadienne pour la période du 1er juin 2002 au 31 mai 2003 a constitué la principale source de données pour l'inventaire. Dans cette base de données sont consignées les dates de début et de fin de chacun des mouvements

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[2] Oxydes d'azote (NO_x), oxydes de soufre (SO_x), hydrocarbures (HC), composés organiques volatils (COV), monoxyde de carbone (CO) et matières particulaires totales (MPT), et fractions de diamètre égal ou inférieur à 10 micromètres (MP_{10}) et 2,5 micromètres ($MP_{2,5}$).

de tous les types de navires marchands évoluant dans les eaux canadiennes, ainsi que les caractéristiques de chaque navire. L'inventaire des émissions s'est limité aux navires marchands transocéaniques jaugeant 400 tonnes brutes ou plus.

Selon la base de données INNAV, 1 789 navires jaugeant plus de 400 tonnes brutes ont effectué un total de 29 603 mouvements en 2002-2003. Ayant jugé que les mouvements des navires «marchands traversiers» étaient sous-estimés, on a rajusté le nombre des mouvements de ces navires au prorata des 47 866 mouvements de traversiers effectués en 2005, selon les chiffres d'Environnement Canada. Ces chiffres étaient fondés sur les horaires des traversiers et sur l'information transmise par les exploitants de traversiers.

Une donnée d'entrée cruciale pour le calcul des émissions des navires faisant route est le temps passé «en route». Ce temps a été calculé pour chaque navire en divisant la distance de port à port dans les eaux canadiennes par la vitesse normale prévue du navire selon son type. Une analyse a été effectuée pour déterminer le nombre de mouvements de navires entre zones portuaires et estimer ainsi les distances parcourues. Aux fins de l'analyse, on a fait une distinction entre les mouvements entre ports intérieurs et les mouvements entre ports intérieurs et internationaux. Les mouvements entre zones portuaires ont été utilisés pour classer les trajets de port à port selon leur «achalandage», et pour déterminer le nombre des trajets de port à port à inclure dans l'analyse pour obtenir différents pourcentages cumulatifs de l'activité totale de navires. Ainsi, pour ce qui est des mouvements intérieurs des navires, 50 % ont lieu entre 49 zones portuaires, et 80 % entre 451 zones portuaires. Pour ce qui est des arrivées en provenance de ports étrangers, 25 ports canadiens comptent pour 50 % des arrivées, et 104 ports pour 80 % des arrivées. Dans cette analyse, les distances de port à port ont été déterminées pour tous les trajets qui représentaient 80 % de tous les mouvements des navires sur des routes intérieures et internationales. Aux fins de l'analyse spatiale, on a aussi déterminé le pourcentage de chacun de ces trajets situé dans les régions 5 à 20. De plus, on a identifié les points d'entrée et de sortie les plus couramment utilisés le long de la limite de 200 milles de la ZEE (zone économique exclusive), et de la frontière Canada/États-Unis dans les Grands Lacs.

Les 20 % restants des voyages des navires dont la distance n'a pas été calculée de façon précise par la méthode ci-dessus représentent environ 4 000 trajets de port à port. Des techniques simplifiées ont été utilisées pour évaluer la longueur de ces trajets. On est d'abord allé puiser dans la banque des distances déterminées pour les 80 % des voyages les plus fréquents, puis on a approximé la longueur d'un trajet en calculant la distance entre le centre de la région «d'émissions» de départ et le centre de la région d'arrivée.

L'inventaire des émissions a été constitué à l'aide d'une version améliorée du système de calcul des émissions des navires océaniques et de données développé pour le compte d'Environnement Canada en 2005. Cette application utilise le logiciel Access™ de Microsoft pour calculer les émissions au moyen d'une méthodologie ascendante qui s'appuie sur les données d'activité de port à port colligées par la Lloyd's pour les navires évoluant dans les eaux canadiennes. Cette application a été modifiée pour utiliser les données du système INNAV et les identificateurs de port, et pour :

- calculer des limites maximales et minimales des niveaux d'émissions, d'après les marges d'erreur des coefficients d'émission et des données d'activité des navires;
- incorporer les mises à jour et les révisions des hypothèses et coefficients d'émission utilisés pour calculer l'énergie produite par les moteurs et la durée de marche de ceux-ci;
- décomposer les résultats pour des cellules de 4 km sur 4 km dans chaque région d'émissions, à l'aide de tableaux de proration spatiale élaborés par les professeurs Corbett et Wang de l'Université du Delaware, dans un format compatible avec celui des modèles régionaux de dispersion atmosphérique.

Des prévisions de base de niveaux d'émissions de référence ont été faites, qui tenaient compte d'une croissance du tonnage des marchandises transportées par navire, d'un remplacement graduel des moteurs des flottes de navires par de nouveaux moteurs respectant la limite d'émissions de NO_x de l'OMI, et de la limitation à 500 ppm de la teneur en soufre du mazout marin vendu au Canada à compter de 2007.

Des coefficients de croissance ont été élaborés pour déterminer approximativement l'évolution des niveaux d'émissions produites par chaque type de navire jusqu'en 2010 et 2020, par rapport à 2002. L'élément utilisé pour représenter la croissance des émissions est le tonnage de marchandises transportées par chaque type de navire. Les coefficients de croissance ont été définis à l'aide de données nationales fournies par Transports Canada sur le tonnage de marchandises transportées en 2002 par type de navire, et des prévisions concernant le tonnage de marchandises devant être expédié par les ports canadiens en 2010 et en 2020. Selon les prévisions actuelles, le tonnage de toutes les catégories de cargaisons intérieures et internationales aura augmenté de 11 % (1,3 % par année) en 2010 et de 21 % (1,1 % par année) en 2020, par rapport à 2002. Ce sont les cargaisons conteneurisées qui devraient croître le plus rapidement, affichant des coefficients de croissance de 1,29 et 1,74, respectivement, de 2002 à 2010 et 2020. Il est prévu que globalement, le taux de croissance réel sera plus élevé que ce que laissent croire les prévisions actuelles, qui sont fondées sur des données limitées relatives à la croissance des activités dans le Port de Montréal et les ports des États-Unis.

L'effet du remplacement graduel des moteurs existants par de nouveaux moteurs conformes à la limite actuelle fixée par l'OMI pour les émissions de NO_x produites par les navires transocéaniques a été évalué au moyen d'un modèle simple développé pour le remplacement de cet équipement. On a supposé que les machines principales et auxiliaires existantes seraient retirées du service à un rythme moyen de 2 % par année et qu'elles seraient remplacées par de nouveaux moteurs conformes aux limites d'émissions de NO_x de l'OMI. On a supposé que la proportion de moteurs à régime lent et de moteurs à régime moyen utilisés pour les machines principales (95 % de moteurs à régime lent et 5 % de moteurs à régime moyen) et la proportion des machines auxiliaires utilisant du mazout intermédiaire et du mazout marin (75 % de résidu de pétrole et 25 % de mazout marin) demeureraient constantes, aux valeurs établies pour l'année de référence. Au taux de remplacement supposé et en admettant que la limite actuelle d'émissions de NO_x établie par l'OMI demeurera la même jusqu'en 2020, on prévoit, pour l'ensemble de la flotte, une diminution du coefficient d'émission moyen de NO_x de 5,7 % pour les machines principales et de 8,3 % pour les machines auxiliaires.

Les émissions ont été évaluées en admettant que toute la zone étudiée serait désignée «zone de contrôle des émissions de soufre» (SECA). Par suite d'une désignation SECA, tous les mazouts lourds utilisés par les navires transocéaniques devront avoir une teneur en soufre d'au plus 1,5 %. On a supposé que la teneur en soufre du mazout marin demeurerait inchangée par rapport à l'année de référence. De même, il a été admis que les émissions de NO_x et le pourcentage de mazout lourd et de mazout marin utilisés pour alimenter les machines auxiliaires demeureraient les mêmes que pour l'année de référence. La diminution de 2,7 % à 1,5 % de la teneur en soufre des mazouts lourds pour les approvisionnements internationaux et de 1,7 % à 1,5 % pour les approvisionnements intérieurs réduira les émissions de particules (des sulfates, par exemple) et des SO_x par les machines principales et auxiliaires. Le pourcentage de réduction des émissions de particules et de SO_x a été évalué à partir de données publiées et appliquées à chaque type de navire visé par l'inventaire, moyennant des rajustements pour la teneur en soufre initiale des carburants utilisés.

Le tableau S-1 résume les niveaux d'émissions de base pour 2002, 2010 et 2020. On prévoit une augmentation de 9 % à 13 % des émissions en 2010 et de 20 % à 29 % en 2020, par rapport à l'année de référence 2002 (voir le tableau S-2). Comme le montre la figure S-2, les

vraquiers, les porte-conteneurs et les citernes sont les trois types de navires qui contribuent le plus aux émissions de dioxyde de carbone et des principaux polluants responsables de la dégradation de la qualité de l'air. Ensemble, ces types de navires comptent pour 67 % à 74 % de toutes les émissions.

L'analyse de la ventilation mensuelle des émissions révèle que c'est de janvier à mars que les émissions sont les plus faibles. À l'inverse, c'est en mai, juillet, août, septembre et octobre que les niveaux les plus élevés sont atteints. Les mois au cours desquels les valeurs maximales ou minimales d'émissions sont enregistrées varient d'un polluant à l'autre.

La désignation d'une SECA dans le secteur étudié devrait entraîner une réduction des émissions de SO_x de 33 % en 2010, et de 24 % en 2020, par rapport à 2002. Elle devrait également réduire les niveaux de sulfates produits par la combustion du soufre présent dans les carburants marins, et contrer la croissance des émissions annuelles de MP_{10} et de $MP_{2,5}$, la faisant passer de 13 % à -5 % en 2010, et de 29 % à 8 % en 2020.

Tableau S-1 – Émissions – année de référence et prévisions

Substance	Émissions				
	2002	2010		2020	
	(tonnes/année)	(tonnes/année)	% aug.	(tonnes/année)	% aug.
CO_2	3 298 991,8	3 696 368,7	12,0 %	4 167 118,0	26,3 %
NO_x	93 699,5	102 334,5	9,2 %	112 209,6	19,8 %
SO_2	47 459,0	53 576,4	12,9 %	61 143,3	28,8 %
VOC	2 843,2	3 210,0	12,9 %	3 644,2	28,2 %
HC	2 843,2	3 210,0	12,9 %	3 644,2	28,2 %
CO	3 092,9	3 432,1	11,0 %	3 834,5	24,0 %
MPT	10 348,4	11 729,0	13,3 %	13 362,4	29,1 %
MP_{10}	8 157,0	9 241,0	13,3 %	10 523,5	29,0 %
$MP_{2,5}$	6 854,8	7 761,8	13,2 %	8 834,9	28,9 %

Tableau S-2 – Émissions prévues en supposant une désignation SECA (zone de contrôle des émissions de soufre)

Substance	Émissions				
	2002	2010		2020	
	(tonnes/années)	(tonnes/année)	% chang.	(tonnes/année)	% chang
CO_2	3 298 991,8	3 696 368,7	12,0 %	4 167 118,0	26,3 %
NO_x	93 699,5	102 284,4	9,2 %	112 209,6	19,8 %
SO_2	47 459,0	31 842,1	-32,9 %	36 214,6	-23,7 %
VOC	2 843,2	3 210,0	12,9 %	3 644,2	28,2 %
HC	2 843,2	3 210,0	12,9 %	3 644,2	28,2 %
CO	3 092,9	3 432,1	11,0 %	3 834,5	24,0 %
PMT	10 348,4	9 835,3	-5,0 %	11 194,9	8,2 %
MP_{10}	8 157,0	7 752,0	-5,0 %	8 819,6	8,1 %
$MP_{2,5}$	6 854,8	6 513,6	-5,0 %	7 406,9	8,1 %

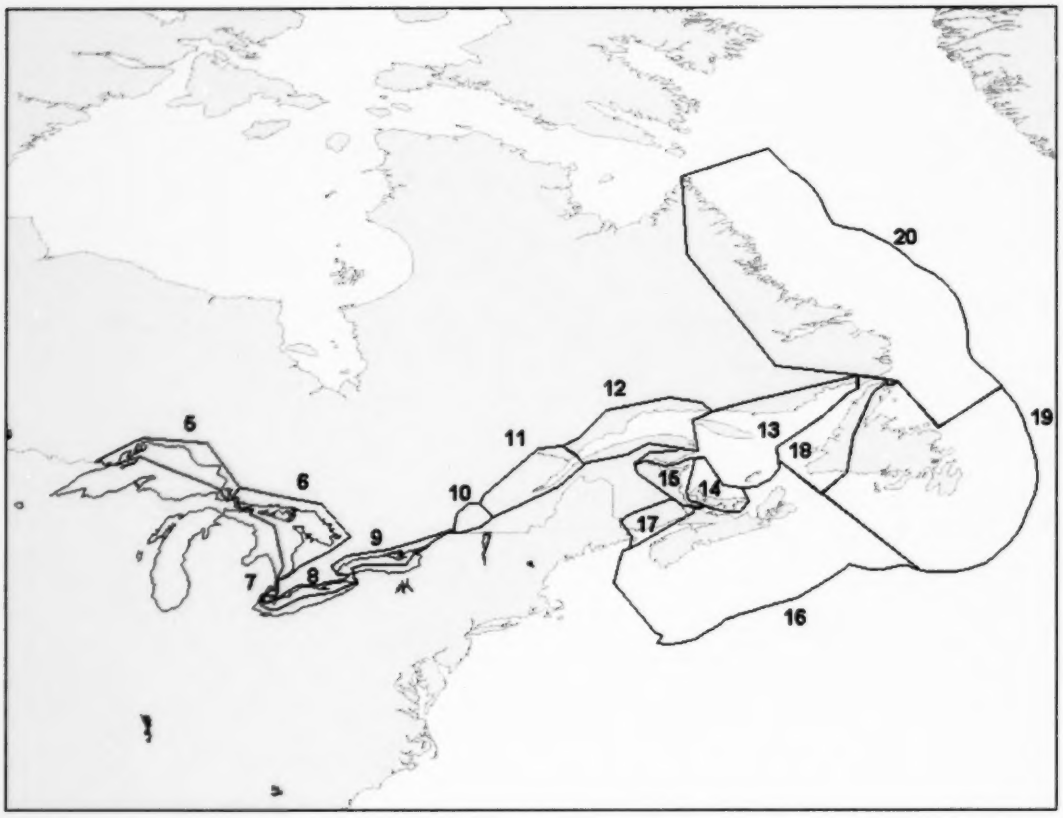

Figure S-1 **Carte de la zone d'inventaire des émissions, décomposée en sous-régions**

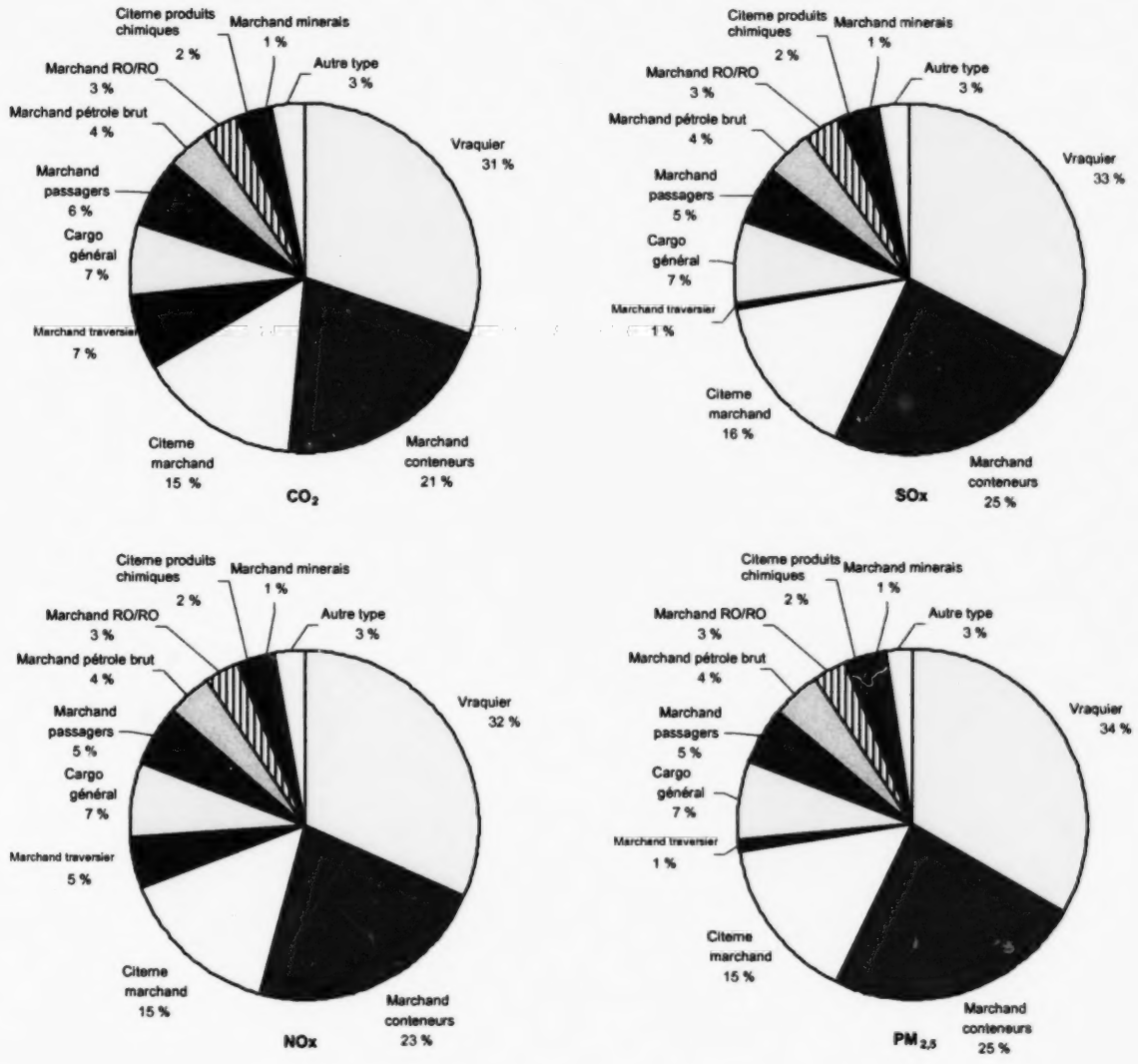

Figure S-2 Répartition des émissions de CO_2, de SO_x, de NO_x et de $MP_{2,5}$ par type de navire, pour 2002

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GLOSSARY

Abbreviation	Definition
bhp-h	Brake horsepower-hour, a unit of work output.
CARB	California Air Resources Board.
CO_2	Carbon dioxide.
cSt	Centistoke, a measure of kinematic viscosity.
DWT	Dead weight tonnage of a vessel
EPA	US Environmental Protection Agency.
g	Gram.
GT	Gross tonnage of a vessel.
HC	Total hydrocarbons.
HFO	Heavy fuel oil.
IMO	International Maritime Organization.
IFO	Intermediate fuel oil. IFO380 is the most commonly used intermediate fuel oil and has a maximum viscosity of 380 cSt at fuel handling temperature. IFO180 is blended from IFO380 by adding marine diesel fuel or marine gas oil and has a viscosity of 180 cSt.
kg	Kilogram.
kn	Knot, a nautical mile per hour.
kWh	Kilowatt-hour, a standard unit of measurement for a unit of work output. 1 kWh = 1000 Wh.
L	Litre, 1000 cm^3.
MDO	Marine diesel oil. Used as a general term for marine distillates of various grades, including DMX, DMA, DMB and DMC.
MGO	Marine gas oil. 100% marine distillate fuel.
MSD	Medium speed diesel engine (typically 400-1000 RPM)
NM	Nautical mile.
NOx	Nitrogen oxides, as NO_2.
PM_{10}	Inhalable particulate matter, particles smaller than 10 microns in equivalent aerodynamic diameter.
$PM_{2.5}$	Fine particulate matter, particles smaller than 2. microns in equivalent aerodynamic diameter.
RO	Residual oil, a category of marine fuels that includes various grades of intermediate fuel oils (see IFO).
Ro-Ro vessel	Vessel designed for roll-on and roll-off of cargo.
RPM	Revolutions per minute.
S	Sulphur.
SECA	Sulphur Emission Control Area as defined by the International Maritime Organiszation under Annex VI of the International Convention for the Prevention of Pollutation from Ships, 1973, as modified by the Protocol of 1978 (often referred to as MARPOL 73/78).
SFC	Specific fuel consumption, as mass of fuel consumed per unit of work output, typically measured in units of g/bhp-h or g/kWh.
SMED	Swedish Methodology for Environmental Data.

Abbreviation	Definition
SOx	Sulphur oxides, as SO_2.
SSD	Slow speed diesel engine (<130 RPM).
t, or tonne	metric tonne, 1000 kilograms.
TPM	Total particulate matter.
ULCC	Ultra large crude carrier.
US	United States of America.
VLCC	Very large crude carrier.
VOC	Volatile organic compounds.
W	Watt of power.
yr	Year.

1. INTRODUCTION

1.1 BACKGROUND

Levelton Consultants Ltd. (Levelton) was retained by Transport Canada to prepare a regional air emission inventory for commercial marine vessels operating on the Great Lakes, the St. Lawrence Seaway, and the East Coast of Canada. Work on this project was guided by a steering committee consisting of staff from Transport Canada and Environment Canada.

The principal tasks completed in this project were:

1. Develop an inventory of emissions of air contaminants and greenhouse gases from commercial marine vessels in 2002 using activity-based information recorded in the Canadian Coast Guard database system for the Great Lakes-East Coast region – The inventory includes lower-bound, best and upper-bound emission estimates determined using bottom-up estimating techniques, and with the best estimate resolved by vessel type, operating mode, and in time and in space.
2. Develop an emission forecast for 2010 and 2020 based on expected changes in activity and emission characteristics of commercial marine vessels (freight growth, technology changes, and future regulations) – The emission forecast has the same spatial resolution as the baseline emission inventory.
3. Develop an emission forecast for SOx and particulate matter in 2010 and 2020 that incorporates the emission reductions that could potentially occur by implementation of a Sulphur Emission Control Area (SECA).
4. Prepare an emission inventory spatially resolved to regional polygons and to 4 km by 4 km grid cells.

1.2 SUBSTANCES INVENTORIED

The pollutants included in the inventory are as follows:

- oxides of sulphur (SO_x), as SO_2.
- oxides of nitrogen (NO_x), as NO_2.
- total particulate matter (TPM).
- inhalable and fine particulate - PM_{10} & $PM_{2.5}$.
- total hydrocarbons (HC).
- volatile organic compounds (VOC).
- carbon monoxide (CO).
- carbon dioxide (CO_2).

1.3 STUDY AREA

The geographical boundaries for the inventory include all Canadian east coast waters and inland waters that constitute the St. Lawrence River and Great Lakes System. The study area is subdivided into 16 regions numbered from 5 to 20, as described in Table 1-1 and illustrated in

Figure 1-1. The regions were established by Environment Canada in a previous study entitled, "National Emission Inventory Tool for the Commercial Marine Sector" (Levelton 2005). The regions include Canadian waters only and are constrained by the Canada-USA border in the Great Lakes, and the international border located at the 200 nautical mile limit of Canada's Exclusive Economic Zone (EEZ) in the Atlantic.

Table 1-1 Emission Regions for Canadian Waters

	Region	Description
5	Lake Superior	Includes the entire lake with the eastern boundary being the western side of Sault Ste. Marie. Sault Ste. Marie is not in this region. Major Port: Thunder Bay
6	Lake Huron/Georgian Bay	Starting at the western side of Sault Ste. Marie this region will include all of Lake Huron and Georgian Bay and will stop at the northern end of Sarnia. Sarnia will not be included in this region. The eastern side of this region will be the Straits of Mackinac separating Mackinaw City and St. Ignace. Major Port: Sault Ste. Marie
7	Lake St. Clair	Region will start at the northern side of Sarnia and stretch to the southern side of Windsor. Both Sarnia and Windsor will be included in this region. Primary Port: Sarnia
8	Lake Erie	Region will start at the southern side of Windsor and include Lake Erie and the Welland Canal. The eastern boundary will be where the Welland Canal enters into Lake Ontario. Major Port: Nanticoke
9	Lake Ontario	Region will include Lake Ontario from the start of the Welland Canal to the Quebec border. Major Port: Hamilton
10	St. Lawrence Seaway	Region will include the area from Quebec border to Contrecoeur, Quebec. This area will include the entire port of Montreal. Major Port: Montreal
11	St. Lawrence River	Region will include the area from Contrecoeur to Les Escoumins.
12	Mouth of St. Lawrence River	Region will extend from Les Escoumins/Trois-Pistoles to western tip of Anticosti Island. Eastern border will be formed by extending a line from Havre-St. Pierre to the western tip of Anticosti Island (Port Menier) and then down to the Cape of Gaspe.
13	Gulf of St. Lawrence (Quebec Region)	Western boundary of this region will be the line between Havre-St. Pierre/Western tip of Anticosti/Gaspe. Northern/Eastern boundary will be the Quebec/Newfoundland border. Southern boundary will be the Quebec border running from Dalhousie (NB) to the Madeleine Islands. Major Port: Havre St. Pierre
14	Prince Edward Island	Boundary is the provincial waters around PEI. Major Port: Charlottetown
15	Gulf of St. Lawrence (New Brunswick)	Regions northern boundary extends from Dalhousie to the point where provincial boundary meets provincial boundary of PEI and Quebec. South-eastern boundary is the provincial boundary between PEI and NB. Major Port: Dalhousie

	Region	Description
16	Nova Scotia (North and Eastern side)	Region will extend from the west at provincial boundary between PEI/NB/Nova Scotia, around the tip of Cape Breton Island. The eastern boundary will be the 200 mile limit. The southern limit will be the international border and the western limit will be the provincial boundary extending out of the Bay of Fundy to the international boundary. Major Port: Halifax
17	Bay of Fundy (New Brunswick)	This region will be the western portion of the Bay of Fundy from the provincial border to the international boundary. Major Port: Saint John
18	Western Newfoundland	The western boundary for this border will be the provincial border between Newfoundland and Quebec. The Northern boundary will be the line running between Red Bay and the tip of Newfoundland. The southern boundary will be the line running over the northern tip of Cape Breton Island and the eastern boundary will be the line running from Burgeo (NF) to the Nova Scotia Border. Major Port: Corner Brook
19	East Shore of Newfoundland	This region will be bounded in the south west by the line from Burgeo (NF) to the Nova Scotia Border, in the south by the Nova Scotia Provincial Boundary, in the east by the 200 nautical mile border and in the north west by the line extending from Fogo to the 200 mile limit. Major Port St. John's
20	North Shore of Newfoundland/Labrador	This region will be bounded in the north by the line running northeast from the Labrador/Quebec border to the 200 mile limit, and south by the line running northeast from Fogo to the 200 mile limit. The eastern boundary will be the 200 mile limit. Major Port: Happy Valley Goose Bay

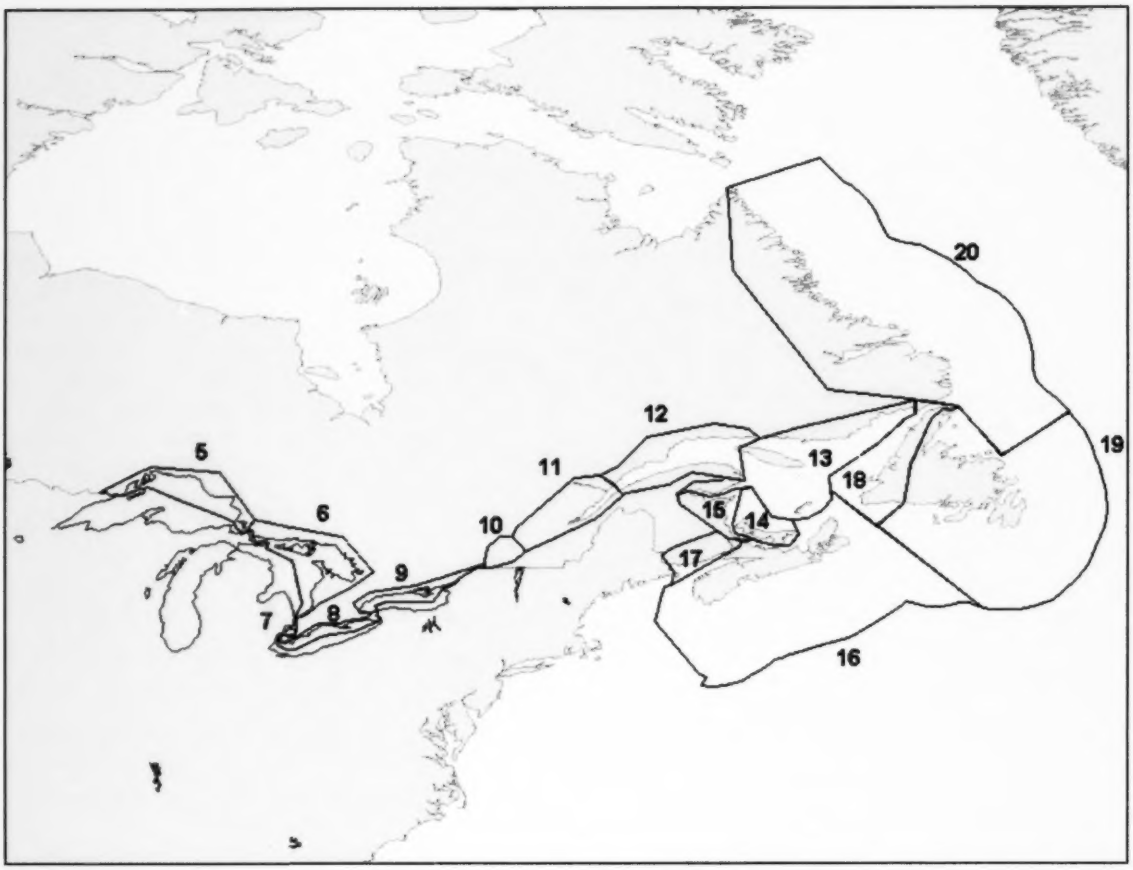

Figure 1-1 **Map of the Emission Regions used to Spatially Resolve the Emission Inventory**

2. METHODOLOGY

2.1 General Method for Calculating Ship Emissions by Mode

Emissions are calculated for marine vessels using an emission factor approach according to the following generalized equation:

$$\text{Emissions for a given pollutant} = \sum [(P \times LF \times EF)_{Main} + (P \times LF \times EF)_{Auxiliary}]_{Mode} \times T_{Mode} \quad (1)$$

Where: P = maximum power output of main or auxiliary engine, kW;

LF = load factor for main or auxiliary engines, as a fraction of maximum installed power capacity for these power systems, dimensionless;

EF = emission factor (pollutant-specific) in mass emitted per work output of the main or auxiliary engine in underway, manoeuvring and hotelling mode, g/kWh; and

T_{mode} = time in underway, manoeuvring or hotelling mode, hours.

Emissions from vessels while underway arise from their main engines and to a lesser extent from their auxiliary engines. Emissions from a vessel in a port area arise from the operation of main and auxiliary engines while the vessel manoeuvers to berth or anchor, and from the auxiliary engines while at anchor or dock.

This calculation method is the accepted approach for individual ocean-going vessels as well as for groups of other types of smaller vessels, as long as the power, emission factor, load factor and time in mode are chosen accordingly. The challenge in such calculations is to determine the appropriate input data that simulate emissions from the diverse characteristics of main and auxiliary power systems and the inherent variability of vessel movement and energy use.

2.2 Assumptions and Calculating Factors

The first area of work completed was to determine the methods and sources of data to be used in the study. The key inputs for emission calculations are emission factors, load factors, cruise and manoeuvring speeds, travel distance between ports and in port, and other assumptions needed to estimate emissions for each type of vessel and operating mode. The assumptions need to reflect operating practices, fuel quality, sulphur content, and vessels used on the Great Lakes and on the East coast of Canada.

A number of marine emission studies were reviewed during the initial phase of the project. The study for the European Commission by Entec UK Ltd. is cited frequently in the literature and is considered to be one of the most comprehensive sources of emission factors and assumptions for most ocean-going vessels. Since the publication of the Entec report in 2002, other agencies have conducted studies of emissions from marine vessels and related vessel characteristics. SMED (Swedish Methodology for Environmental Data) published updated emission factors in 2004 based on an expanded database of exhaust measurements. (SMED's reported factors are in close agreement with Entec except for VOCs and PM.) In North America, recent studies of emissions in major American ports conducted by the Starcrest Consulting Group have utilized emission factors from the European studies in combination with port-specific information gathered from surveys of vessels. Under contract from the United States EPA, ICF Consulting conducted a review of best practices for the preparation of port emission inventories, with a strong focus on the most recent methods applied to emissions from major United States ports, which is currently in draft status. The California Air Resources Board (CARB)has produced an

emission estimation methodology document for use in California that summarizes data from their 2005 Ocean-Going Vessel Survey and draws from available information to present standard methods for estimate emissions from ocean-going vessels. Dr. James Corbett from the University of Delaware has conducted research for many years on emissions from marine vessels and shared information with this project from his work for the US-Canada team that is engaged in developing a North American marine emission inventory and an application to the International Maritime Organization (IMO) for the designation of a Sulphur Emission Control Area (SECA) for maritime regions of North America.

Table 2-1 summarizes the sources considered for the key emission parameters needed in this study. References used for assumptions and emission inventory parameters are cited throughout the text and listed at the end of this report.

Table 2-1 Sources of Emission Estimation Parameters and Assumptions

Reference Studies	Emission Factors	Load Factors	Speeds	Auxiliary Engines	Fuels Used
Entec UK Ltd.	x				x
Swedish Methodology for Environmental Data (SMED)	x				x
Dr. James Corbett	x	x			
Starcrest Consulting Group		x	x	x	
ICF (EPA)		x	x	x	x
California Air Resources Board (CARB)	x				
Levelton Consultants Ltd.		x	x		x

2.2.1 Emission Factors

There are two primary subcategories of main engines - slow speed and medium speed engines - each with characteristic emission factors and commonly used fuel types. Slow speed engines (<130 revolutions per minute (rpm)) are two-stroke engines and are used on 95% of all ocean-going vessels, according to survey data from for the Port of Los Angeles (CARB, 2005). Medium speed engines (typically >400 rpm) comprise the remaining 5% of main engines. The distribution of engine types for ocean-going vessels in Canada is expected to be similar to that observed for the Port of Los Angeles. From a 2005 survey of the characteristics of ocean-going vessels conducted by the BC Chamber of Shipping, essentially all main engines of container ship and 97% of main engines of coal carriers calling at the Port of Vancouver were two stroke (slow speed) designs.

Auxiliary engines are commonly medium speed four stroke diesel engines and this is confirmed in the 2005 BC Chamber of Shipping survey data.

Emission factors vary depending on the fuel quality used in marine engines. The two common fuels used in diesel engines are marine diesel oil (MDO) and heavy fuel oil (HFO), with HFO commonly blended with distillate to produce intermediate fuel oils (IFO) with improved viscosity and characteristics. According to a 2005 survey of fuels used by ocean going vessels calling at California ports (CARB, 2005) and information from the 2005 survey by the BC Chamber of Shipping, 99% or more of main engines use Intermediate fuel oils. The same California survey found 25% of auxiliary engines in ocean-going vessels used marine distillate and 75% used HFO.

The most recent emission factors in the literature for the predominant engine/fuel combinations are summarized in Table 2-2, together with composite emission factors for each operating mode. The composite emission factors for main engines assume 95% of the engines use HFO, which may be an under-estimate for Canadian ports. A higher proportion of HFO use would only affect the SOx emission factor significantly. The composite emission factors for auxiliary engines assume a fuel mix of 25% MDO at 1% S and 75% HFO at 2.7% S, for a weighted average of 2.3%, which is in the range of 2.2-2.5% reported by vessels for auxiliary engines in the 2005 BC Chamber of Shipping survey of fuels and engines used on container ships and coal carriers. Emission factors can be converted from g/kWh to g/tonne fuel burned by dividing the factors shown by the specific fuel consumption rates for each engine and fuel combination.

The SOx emission factors for ocean-going vessels in Table 2-2 apply to vessels fuelled entirely with fuels of the sulphur content shown. Adjustments were made for vessels using a mix of international and domestic fuels of lower sulphur content as explained later in this section.

Table 2-2 Emission Factors for Main and Auxiliary Engines by Mode

Engine Type	Source	Weighting Factor	Fuel Type	Sulphur Content*	SFC g/kWh	NOx g/kWh	SOx g/kWh	HC g/kWh	VOC g/kWh	PM g/kWh	PM_{10} g/kWh	$PM_{2.5}$ g/kWh	CO g/kWh	CO_2 g/kWh
Ocean-Going Vessels														
Main Engine														
Underway														
Slow speed	1,2,4	0.95	HFO	2.7	195	19.5	10.5	0.6	0.6	2.4	1.9	1.5	0.5	620
Medium speed	1,2	0.05	HFO	2.7	213	14	11.5	0.5	0.5	0.8	0.6	0.5	1.1	677
Composite			Avg	2.7	196	19.2	10.6	0.6	0.6	2.3	1.8	1.5	0.5	623
Manoeuvring														
Slow speed	1,2	0.95	HFO	2.7	215	14.5	11.6	1.8	1.8	2.4	1.9	1.5	1	682
Medium speed	1,2	0.05	HFO	2.7	234	11.2	12.7	1.5	1.5	1.5	1.2	1	2.2	745
Composite			Avg	2.7	216	14.3	11.7	1.8	1.8	2.4	1.9	1.5	1.1	685
Auxiliary Engines														
All modes														
Medium speed	1,2	0.75	HFO	2.7	227	14.7	12.3	0.4	0.4	1.5	1.2	1	0.9	722
Medium speed	1,2,3	0.25	MDO	1.0	217	13.9	4.3	0.4	0.4	0.4	0.4	0.4	0.9	690
Medium speed	1,2,3	0.0	MDO	0.5	217	13.9	1.1	0.4	0.4	0.3	0.2	0.2	0.9	690
Composite			Avg	2.3	224	14.5	10.3	0.4	0.4	1.2	1	0.9	0.9	713
Ferries & Tugs														
Main Engine														
Underway														
Medium speed	1,2	0.76	MDO	0.17	203	13.2	0.7	0.2	0.2	0.2	0.2	0.2	1.1	645
High speed	1,2	0.24	MDO	0.17	203	12	0.7	0.2	0.2	0.2	0.2	0.2	1.1	645
Composite				0.17	203	12.9	0.7	0.2	0.2	0.2	0.2	0.2	1.1	645
Manoeuvring														
Medium speed	1,2	0.76	MDO	0.17	223	10.6	0.8	0.4	0.4	0.2	0.2	0.2	2.2	710
High speed	1,2	0.24	MDO	0.17	223	9.6	0.8	0.4	0.4	0.2	0.2	0.2	2.2	710
Composite				0.17	223	10.4	0.8	0.4	0.4	0.2	0.2	0.2	2.2	710
Aux Engines -All modes														
Medium speed	1,2	0.76	MDO	0.17	217	13.9	0.7	0.4	0.4	0.2	0.2	0.2	0.9	690
High speed	1,2	0.24	MDO	0.17	217	10.9	0.7	0.4	0.4	0.2	0.2	0.2	0.8	690
Composite				0.17	217	13.2	0.7	0.4	0.4	0.2	0.2	0.2	0.9	690

* For sulphur content shown. These were adjusted to reflect the fraction of vessels using North American and international fuel sources, as discussed below.

Sources: 1. ENTEC, 2002 – Fuel type, SFC, NOx, SOx, HC, PM, PM_{10}, CO_2.; 2. SMED, 2004 – $PM_{2.5}$, CO; 3. Starcrest, 2004 – $PM_{2.5}/PM_{10}$
4. MAN B&W, 2004 –NOx emissions from 2-stroke slow speed engines.

The emission factors adopted for this study are consistent with those recommended by Dr. James Corbett, who is currently developing a North American marine emission inventory for CARB and other agencies.

The properties of fuels assumed for calculation of SOx and CO_2 emission factors are listed in Table 2-3.

Table 2-3 Assumed Fuel Properties for International and Domestic Ocean-going Vessels

Fuel Quality	Assumed Source	Sulphur Content (wt%)	Carbon Content (%)	Density (kg/L)
HFO	International*	2.7	86.7	0.965
MDO	International*	1.0	86.7	0.9
MGO	International*	0.5	86.7	0.852
IFO	Domestic**	1.7	-	-
MDO-General	Domestic**	0.17	-	-
MDO-Military	Domestic**	0.25	-	-

Source: * Entec, 2002, ** Environment Canada, 2006.

SOx emission factors vary in proportion to the sulphur content of the marine fuel burned. Since marine fuels sold in Canada tend to have lower sulphur contents, on average, than the marine fuels being used by ocean-going vessels that bunker fuels on the international market, an adjustment of the SOx emission factors is appropriate for vessels travelling all or most of the time between ports in North America. The vessels tracked in the INNAV data base were segregated into two groups: vessels that visited ports outside North America at some time during the inventory year; and vessels that only visited ports within North America. The cumulative main engine horsepower was then totalled for each of these two groups of vessels.

Composite weighting factors were developed for each type of vessel to estimate the proportion of international and domestic marine fuels consumed. For each type of vessel, the composite weighting factor for fuels assumed to have the international average fuel sulphur content was determined as the percentage of cumulative main engine horsepower on vessels that visited at least one port outside North America. The remainder of the vessels of the same type were assumed to burn fuels having a sulphur content equal to the average in Ontario, Quebec and the Atlantic provinces. The international and domestic average sulphur contents assumed for this analysis are given in Table 2-3. The weighting factors and the resulting composite SOx emission factors for each vessel class after adjustment for fuel sulphur content are presented in Table 2-4.

2.2.2 Load Factors

Load factors are expressed as a percent of a vessel's total power and are commonly estimated from test programs or by survey of marine vessel owners/operators and applied as a constant by mode of operation and ship type. General load factor assumptions are available in the reviewed literature, and were assigned to the appropriate INNAV vessel type as indicated in Table 2-5. Consistent with the CARB and Starcrest reports, main engines were assumed to operate in underway and manoeuvring modes only, while auxiliary engines were assumed to operate in all three operating modes. Data from the emission inventory for the Port of Los Angeles (Starcrest, 2004) was used to derive main engine manoeuvring load factors based on a weighted average of observed inbound, outbound and docking load factors.

Table 2-4 SOx Emission Factors for Composite Average Sulphur Content

Vessel Class	INNAV Code	Percent Fuel Source		SOx Emission Factor (g/kWh)		
		Domestic*	International	Main Engine		Auxiliary Engine
				Underway	Manoeuvring	All Modes
Merchant (Dry)	MM	0	100	10.6	11.7	10.3
Merchant (Tanker)	TT	25	75	9.6	10.6	9.2
Merchant Auto	MA	10	90	10.2	11.3	9.9
Merchant Bulk	MB	20	80	9.8	10.8	9.4
Merchant Chemical	TL	5	95	10.4	11.5	10.1
Merchant Coastal	MS	45	55	8.8	9.7	8.3
Merchant Container	MC	5	95	10.4	11.5	10.1
Merchant Crude	TC	20	80	9.8	10.8	9.4
Merchant Ferry	MF	100	0	0.7	0.8	0.7
Merchant Gasoline	TG	0	100	10.6	11.7	10.3
Merchant General	MG	10	90	10.2	11.3	9.9
Merchant Liquified Gas	TQ	40	60	9.0	9.9	8.5
Merchant Molasses	TM	0	100	10.6	11.7	10.3
Merchant Ore	MO	20	80	9.8	10.8	9.4
Merchant Ore/Bulk/Oil	TO	5	95	10.4	11.5	10.1
Merchant Passenger	MP	55	45	8.5	9.3	7.9
Merchant Reefer	MR	0	100	10.6	11.7	10.3
Merchant RO/RO	MH	10	90	10.2	11.3	9.9
Merchant Super Tanker	TS	0	100	10.6	11.7	10.3
Merchant ULCC	TU	0	100	10.6	11.7	10.3
Merchant VLCC	TV	0	100	10.6	11.7	10.3
Tugs Ocean	HO	80	20	2.7	3.0	2.6
Warship - General	WR	100	0	1.0	1.1	1.1
Warship Surface	WS	100	0	1.0	1.1	1.1

* Approximate cumulative percentage of main engine power capacity on vessels of each type reporting no visits to ports outside Canada and the United States.

The auxiliary engine load factors are based on data from Starcrest (2004), which conducted interviews with ship captains and engineers during vessel boarding programs for the inventory of emissions in the Port of Los Angeles. The load on an individual auxiliary engine is typically in the range of 60 – 75% while it is in operation. The values reported in Table 2-5 are lower than this because they represent the fraction of total installed auxiliary engine power. Ocean-going vessels are equipped with multiple auxiliary engines (see Table 2-6) and only a fraction of the total installed capacity is utilized in each mode of vessel operation to suit power demands. For example, assume a vessel is equipped with the following auxiliary engines and has a power demand when underway of 300 kW:

Aux Engine 1: 400 kW
Aux Engine 2: 500 kW
Aux Engine 3: 1500 kW
Total: 2400 kW

Therefore, the ship's engineer would choose to operate Aux Engine 1 at 75% load to generate 300 kW so that this engine is operated in its optimum design range. The remaining engines would be shutdown. In this example, the overall load factor, as used for the emission inventory analysis, would be:

Load Factor = 300 kW/2400 kW x 100 = 13% of the total installed auxiliary power. (2)

There is potential for considerable uncertainty in load factors for auxiliary engines on a trip by trip basis and there is limited monitoring data available from which to calculate average load factors for these engines by class of vessel. A comprehensive data base of information on vessel characteristics, engine capacities, load factors and fuels used is being developed by the BC Chamber of Shipping through collection of responses to a survey of ocean-going vessels, which was initiated in 2005. Preliminary analysis of survey responses provided by container vessels and coal carriers in 2005 (Levelton, 2006) found that the average load factor for auxiliary engines while at berth was 36-40% for container vessels and 39-43% for coal carriers. These values are similar to the 40% estimated by Entec (2002), but substantially higher than the values estimated for the Port of Los Angeles. For consistency, the values from the Port of Los Angeles have been used in this study, however, future updates of emissions from marine vessels in Canada should reconsider the assumed load factors and take into account the latest information available from ship surveys.

Table 2-5 Load Factors for Main and Auxiliary Engines for Each Class of Vessel

Vessel Class	Main Engine		Auxiliary Engine		
	Underway	Manoeuvring	Underway	Manoeuvring	Dockside
Merchant (Dry)	75%	5%	17%	45%	22%
Merchant (Tanker)	75%	8%	13%	45%	67%
Merchant Auto	80%	6%	13%	67%	24%
Merchant Bulk	75%	8%	17%	45%	22%
Merchant Chemical	75%	8%	13%	45%	67%
Merchant Coastal	80%	5%	17%	45%	22%
Merchant Container	80%	3%	13%	50%	17%
Merchant Crude	75%	8%	13%	45%	67%
Merchant Ferry	80%	40%	50%	50%	40%
Merchant Gasoline	75%	8%	13%	45%	67%
Merchant General	80%	5%	17%	45%	22%
Merchant Liquified Gas	75%	8%	13%	45%	67%
Merchant Molasses	75%	8%	13%	45%	67%
Merchant Ore	75%	8%	17%	45%	22%
Merchant Ore/Bulk/Oil	75%	8%	13%	45%	67%
Merchant Passenger	55%	6%	80%	80%	64%
Merchant Reefer	80%	4%	20%	67%	34%
Merchant RO/RO	80%	9%	15%	45%	30%
Merchant Super Tanker	75%	8%	13%	45%	67%
Merchant ULCC	75%	8%	13%	45%	67%
Merchant VLCC	75%	8%	13%	45%	67%
Tugs, Ocean	80%	9%	17%	45%	22%
Warship – General	80%	10%	17%	45%	22%
Warship Surface	80%	10%	17%	45%	22%

2.2.3 Auxiliary Engines

Auxiliary engine power is not provided in the INNAV data base available for this study. Ratios of auxiliary power to main engine power were calculated from average main and auxiliary engine power ratings reported by Starcrest for the Port of Los Angeles (PoLA) inventory and are summarized in Table 2-6. These ratios were used in conjunction with the main engine power capacity in the INNAV data to determine the auxiliary engine capacity for each vessel.

Table 2-6 Auxiliary Engine Power Ratios

Vessel Class	Average Main Engine Power (kW)	Auxiliary Engines			Ratio of Auxiliary to Main Engine Power
		Number of Engines	Average Power of Each Engine (kW)	Total Power (kW)	
Auto Carrier	10,683	2.95	687	2,027	0.19
Bulk Carrier	7,954	3.02	387	1,169	0.147
Container Ship	30,885	3.78	1,520	5,746	0.186
Cruise Ship	39,563	5	2,200	11,000	0.278
General Cargo	9,331	3.08	577	1,777	0.19
Miscellaneous*	6,252	4	420	1,680	0.269
Tugs, Ocean	2,000	2	125	250	0.125
RORO	10,993	2.04	2,447	4,992	0.454
Reefer	9,567	4	325	1,300	0.136
Tanker	9,409	2.94	675	1,985	0.211

* The factor for miscellaneous vessels was used for Merchant Ferry.

Applying the auxiliary to propulsion ratios to the average main engine power for each class of vessel in the 2002-2003 12-month INNAV data set yields the following typical average auxiliary power capacities (Table 2-7):

Table 2-7 Derived Average Auxiliary Engine Power for Vessel Classes Identified in the INNAV Dataset

Vessel Class	Average Main Engine Power (kW)	Average Auxiliary Engine Power (kW)
Merchant (Dry)	1,607	236
Merchant (Tanker)	9,353	1,973
Merchant Auto	10,530	2,001
Merchant Bulk	7,931	1,166
Merchant Chemical	6,943	1,465
Merchant Coastal	7,170	1,362
Merchant Container	23,988	4,462
Merchant Crude	13,461	2,840
Merchant Gasoline	10,171	2,146
Merchant General	5,728	1,088
Merchant Liquified Gas	13,068	2,757
Merchant Molasses	6,417	1,354
Merchant Ore	12,022	1,767
Merchant Ore/Bulk/Oil	10,940	2,308
Merchant Passenger	18,351	5,102
Merchant Reefer	5,700	775
Merchant RO/RO	11,251	5,108
Merchant Super Tanker	20,477	4,321
Merchant ULCC	26,778	5,650
Merchant VLCC	21,594	4,556
Tugs, Ocean	6,275	784
Warship – General	N/A	1,777
Warship Surface	N/A	1,777

2.2.4 Vessel Service Speeds

Vessel speeds were obtained directly from the INNAV data set for the vast majority of vessels. Although the speed records were generally well-populated, some gaps and zero values were noted. To correct for these cases, a typical vessel speed for each class of vessel included in the inventory was derived. Typical speeds were obtained from previous analysis of upbound vessel transits on the St. Lawrence River between Les Escoumins and Sainte-Pétronille (Eastern end of Orleans Island). Based on reported vessel passage times at Les Escoumins and Sainte-Pétronille, the duration of all individual vessel transits was calculated for 2001. The total distance in nautical miles (NM) between Les Escoumins and Sainte-Pétronille (119 NM) was then divided by the duration to obtain the speed of each vessel on each transit. An average speed by vessel type was thus calculated. Because these transits were made upbound against the flow of the river, 2 knots were added the average speeds to reflect open sea navigation speeds.

Because some vessel classes do not regularly travel into the St. Lawrence, an estimation of the speed at which they travel was based on comparable vessel classes and operational characteristics. In the specific case of cruise ships, a nominal speed of 20 knots was attributed because the average speed of these vessels on the St. Lawrence (9 knots) reflects more the nature of their activities in the river (landscape and whale watching) than normal sailing speed. Master mariners with Maritime Innovation then validated these speeds.

Table 2-8 presents the default speeds obtained by this methodology.

Table 2-8 Typical Vessel Service Speeds

Vessel Class	Service Speed (knots)
Merchant (Dry)	13.6
Merchant (Tanker)	12.5
Merchant Auto	19.8
Merchant Bulk	13.6
Merchant Chemical	13.6
Merchant Coastal	13.3
Merchant Container	18.9
Merchant Crude	13.4
Merchant Ferry	15.0
Merchant Gasoline	16.1
Merchant General	13.3
Merchant Liquified Gas	13.6
Merchant Molasses	12.8
Merchant Ore	14.2
Merchant Ore/Bulk/Oil	11.8
Merchant Passenger	20.0
Merchant Reefer	19.8
Merchant RO/RO	16.5
Merchant Super Tanker	13.8
Merchant ULCC	13.8
Merchant VLCC	13.8
Tugs, Ocean	10.2
Warship - General	10.4
Warship Surface	10.4

2.2.5 Dead Weight and Gross Tonnage Correlations

The U.S. EPA (2000) derived regression equations that estimate vessel horsepower as a function of either dead weight tonnage (DWT), or a combination of DWT and speed, and recommended the set of correlations based on DWT, as shown in Table 2-9. Other correlations were also developed by the US EPA using different approaches, but only the recommended correlations are shown here. To apply these correlations, the emission tool extracts information on DWT during the pre-processing step and estimates engine horsepower as a function of DWT for any vessels where engine horsepower is not directly available.

Table 2-9 Correlation between Horsepower and Deadweight Tonnage (DWT)

*Horsepower = DWT * DWT Coefficient + Intercept*				
Vessel Class	**Sample Size**	**Intercept**	**DWT Coefficient**	**R^2**
Auto Carrier	157	7602	0.4172	0.176
Bulk Carrier	1644	6726	0.0985	0.55
Container	489	-749.4	0.8	0.59
General cargo	641	3046	0.288	0.56
Passenger	40	-4877	6.81	0.72
Reefer	160	1364	1.007	0.58
RORO	110	4358	0.5364	0.76
Tanker	861	6579	0.1083	0.66

Source: US EPA, 2000

For cases where the DWT field is blank, but gross tonnage is provided, the regression in Table 2-10 was applied to estimate the DWT based on the gross tonnage. The estimated DWT was then used as an input to the regressions in Table 2-9 to estimate the installed maximum horsepower for the type of vessel.

Table 2-10 Correlation between Deadweight Tonnage (DWT) and Gross Tonnage (GT)

*DWT = GT * GT Coefficient*		
Vessel Class	**GT Coefficient**	**R^2**
Tankers	1.87	0.99
Bulk Carriers	1.83	0.99
General cargo	1.39	0.93
Container	1.09	0.94
RoRo / Ferry / Cargo	0.54	0.54
Passenger Ship	0.18	0.78

Source: US EPA, 2000.

2.3 Vessel Movement and Duration Data

The Canadian Coast Guard tracks vessel movements within Canadian waters using their INNAV database system. The INNAV database is a detailed source of vessel activity data and the records for the Great Lakes and East Coast of Canada were used in this study. For compatibility, the INNAV data was provided in a format that matches the structure of the input tables in the emission tool. Some adjustments were needed to fine-tune the data format for compatibility.

The time frame for the study was selected to coincide as closely as possible with the calendar year 2002. With approval from the project steering committee, it was decided to prepare the inventory for a 12 month period from June 1 2002 to May 31 2003. This was recommended over

the use of data from earlier in 2002 that originated from the Coast Guard's Data Acquisition and Display, ECAREG and NORDREG datasets for the study area, which are not fully consistent with the data stored in the INNAV database and could result in duplication and/or missing data.

2.3.1 Vessel Movements

The categories of ocean-going ships included in the inventory are commercial marine vessels with a gross tonnage of 400, or greater, which are normally used for cargo or passenger transport. Excluding merchant ferries, a total of 1,789 vessels in the INNAV database met this criterion, which conducted a total of 29,603 movements in the study time period (Table 2-11).

Table 2-11 Number of Vessels and Vessel Movements

Vessel Class	Vessels	Movements
Merchant (Dry)	2	5
Merchant (Tanker)	307	5088
Merchant Auto	24	129
Merchant Bulk	652	12715
Merchant Chemical	65	867
Merchant Coastal	3	40
Merchant Container	157	2867
Merchant Crude	62	500
Merchant Gasoline	2	8
Merchant General	296	2672
Merchant Liquified Gas	3	7
Merchant Molasses	2	7
Merchant Ore	6	152
Merchant Ore/Bulk/Oil	21	119
Merchant Passenger	48	2543
Merchant Reefer	36	110
Merchant RO/RO	44	698
Merchant Super Tanker	5	25
Merchant ULCC	1	7
Merchant VLCC	13	69
Tugs Ocean	20	920
Warship - General	5	14
Warship Surface	13	37
Unknown	2	4
Total	1789	29603

In addition, major ocean-going ferries were included in the emission inventory. Records of movements of ferries are under-reported in the INNAV data. To correct this situation, the reported ferry vessel movements were scaled up to fit the estimated number of movements that would have been made according to ferry schedules. Based on data compiled by Environment Canada, the total number of ferry movements on the Great Lakes and the Atlantic coast in 2005 was approximately 47,866, but only 6,421 movements are included in the INNAV database for 2002. The number of ferry movements is unlikely to have changed dramatically between these

two years. To fill the gap between the recorded and expected actual ferry movements, some manual modification to the INNAV data was done as follows:

1. Ferry movements were grouped by vessel identification code and by route, matching them with data provided by Environment Canada for 2005. The number of ferry vessel movements recorded in the INNAV data was scaled to agree with the 2005 estimate provided by Environment Canada by applying a scaling factor. For example, for the ferry 'Princess of Acadia' (IMO number 7039567), the number of movements in the INNAV database is 328, but the number of movements according the vessel schedule is 1200. The scale-up factor for this vessel is 4 (1200 divided by 328). For ferries with no movements recorded in a month when the ferry would normally be operating, one round-trip movement record was added manually and then the appropriate scaling factor was applied to yield the reported ferry movements and estimate the emissions in that month. The scale-up factors for each ferry are stored in a table called 'ScaleFactors'.

2. For ferries incorrectly reporting the same names for the ports of origin and destination, port names were checked and revised manually to ensure the correct port names were used. This enabled the marine inventory tool to calculate the emissions from all three operation modes - underway, manoeuvring, and hotelling mode

Analysis was conducted to determine the number of vessel movements between port areas and develop an appropriate technique for estimating transit distances. Movements between domestic ports and between domestic and international ports were considered in this analysis in two separate groups. The vessel movements between port areas were used to rank the port-to-port routes by activity level and determine the number of port-to-port routes that would need to be included to yield certain cumulative percentages of total vessel activity. For domestic vessel movements, 50% of vessel movements occur between 49 ports areas and 80% occur between 451 port areas (Figure 2-1).

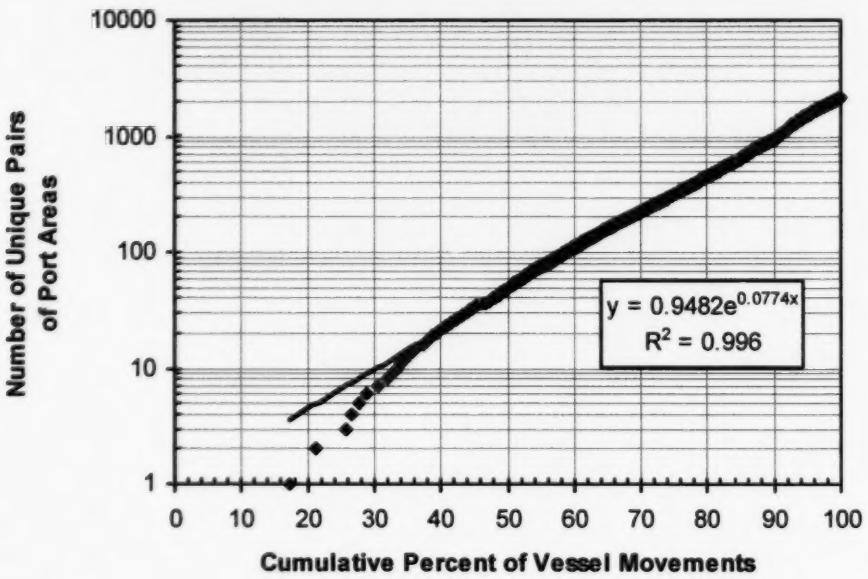

Figure 2-1 Distribution of Vessel Movements Between Domestic Ports

For arrivals from foreign ports, 50% of all vessel movements are to 25 Canadian ports and 80% are to 104 Canadian ports. Based on this analysis, a list covering 80% of vessel movements between ports was provided to Maritime Innovation, which then developed estimates of vessel transit distances for domestic and international trips and the percentages of these distances present in regions 5 to 20. Entry and exit points were determined along the 200-mile EEZ limit and the Canada/USA border in the Great Lakes.

Table 2-12 lists the 11 busiest Canadian ports in the study region that represent approximately 50% of total vessel arrivals.

Table 2-12 Top 11 Busiest Ports in Study Area with 50% Cumulative Movements

Port	Location Code	Vessel Movements		Cumulative Percent
		Number	Cumulative	
Montreal	MTL	2460	2460	12.3
Halifax	HLX	1660	4120	20.6
Québec	QBC	1131	5251	26.3
Saint John	SNB	949	6200	31.1
Dartmouth	DRT	909	7109	35.6
Sorel	SOR	727	7836	39.2
Hamilton	HAM	596	8432	42.2
Sept-Iles	SEP	512	8944	44.8
Nanticoke	NAN	500	9444	47.3
Port-Cartier	PCA	418	9862	49.4
Sarnia, Ontario	SIA	377	10239	51.3

2.3.2 Ship Transit Distances Between Ports for Domestic and International Routes

From the east coast to the western tip of Lake Superior, shipping routes were selected that followed courses commonly used by commercial ocean-going ships. In order to reduce as much as possible the number of possible routes, inbound and outbound traffic were merged into one route. In some cases, the identified routes were located in United States waters, close to the border. These trips were assumed for the purposes of this study to occur in Canadian territory. This situation is limited to the Seaway and some parts of the Great Lakes where the emissions will affect Canada regardless of which side of the border the route is located.

Domestic routes

The first step consisted of establishing the main domestic navigation routes. Then, the distances between each port along the main route was calculated to obtain a total length from origin to destination. For the northern destinations/origins, the farthest point is the northern limit of zone 20. Port positions to/from these routes also served for the international routes.

International

International route distances were calculated in two steps. The first step consisted of calculating distances for overseas and US Atlantic coast origins/destinations. The second step consisted in calculating distances for trips having an origin or a destination in a US Great Lakes port. In the first step, routes were determined according to the Canadian port of origin and the exit point at the Canadian Exclusive Economic Zone (EEZ) limit. The exit point was established based on normal navigation routes published by the British Admiralty.

For the intra-lake trips, the connecting point on the US border was selected in order to connect it with the main routes used in the domestic traffic calculation. For a few ports, the routes did not follow these connecting points and were custom designed.

2.3.3 Adjustments to Fill Gaps in the Movement Data Set

The methodology for estimating trip distances and the subsequent vessel emissions is based on a port-to-port analysis of trip distances. A number of routes in the INNAV data terminated at intermediate locations such as a water area ('W') or other offshore reporting location ('O'). A pre-processing routine was developed to combine these routes into one complete movement terminating at a port. This was accomplished by arranging the movements in sequence for each vessel and analyzing the movement records before and after a 'W/O' type movement to identify opportunities to combine routes.

The distance estimates provided by Innovation Maritime covered 80% of the domestic and international vessel movements and account for 934 routes. These records were uploaded to the route distance table in the emission tool. The remaining 20% of the movements account for approximately 4,000 port to port routes. To estimate distances for the remaining routes a simplified technique was applied. From the known distances in the 80% data set, average distances for region-to-region pairs were calculated. These averages were used to fill gaps in identical route combinations in the 20% data set. This technique was completed for national and international routes. Upon completion, approximately 150 domestic routes and 500 international routes remained with unknown distances. For the remaining national routes, a representative transit distance was estimated between ports in each region based on chart measurements and judgement. The route distances for unknown trip pairs were estimated using a regional centroid-to-centroid approximation. For the remaining international routes, route distances were estimated based on known routes to countries of similar geographic area that share the same entry/exit point to Canadian waters. Application of these averaging techniques resulted in distance estimates for 3,384 routes. It should be noted that there is a higher level of uncertainty in the distance estimates for the bottom 20% of ranked route movements than the values measured directly in Maritime Innovation for the top 80% of movements.

2.3.4 Quality Assurance of Vessel Movement Data

After the techniques described above were applied to fill gaps in the movement data set, the processing routines in the emission tool were initiated to check data quality. The first step the marine emission tool undertakes is a preprocessing routine that checks the input data for gaps in key fields including vessel power, speed, and route specifics. If insufficient data is detected, the record is written to a rejected records table. The second step is the emission calculation routine. Fields checked during this step include: emission factor, load factor, route assignment (spatial), and port activity profile. If any of these parameters are incomplete, the program skips the calculation, writes the skipped record to a reject table and moves on to next record. The records rejected from these processes can be reviewed and adjusted if possible to improve the quality of the data set. The following summary describes the results of these processes:

Preprocessing Summary (excluding ferries)

Total number of vessel movements before preprocessing: 29,603

Movements rejected due to data gaps or out of range values: 322

Movements rejected due to innocent passage: 1,654

Movements ('W/O' types) combined with others: 489

Movements rejected due to incomplete movement records: 1,046

Emission Calculation Summary (excluding ferries)

Total number of vessel movements after preprocessing: 26,092

Movements rejected due to occurrence outside of study area: 197

International movements rejected due to unknown country codes or unknown routes: 514

Movements to/from America rejected due to unknown routes: 41

Domestic movements rejected due to unknown routing info: 1

2.3.5 Ship Manoeuvring Distances in Domestic Ports

Ship manoeuvring distances in domestic ports depend on vessel propulsion equipment such as engine horse power, bow thrusters, stern thrusters, propulsion type (fixed or variable pitch), and Azipod®, as well as operational and human factors. Examples of operational factors that affect manoeuvring distances are the use or not of a tug, weather conditions during the docking operation, and manoeuvring at night or by daylight. Human factors such as the ship's master, preferred docking methods, knowledge of the port, or assistance or not from a pilot can all impact the manoeuvring distance.

Ship manoeuvring distance estimates were based on the experience of two master mariners and are summarized in Table 2-13. This approach yields representative values for the various ship types for a one-way trip. These distances are approximations to actual ship movements, which vary because of the factors mentioned above.

Table 2-13 Average One-Way Manoeuvring Distance by Vessel Class

Vessel Class	Manoeuvring Distance (nautical miles)
Merchant (Dry)	1
Merchant (Tanker)	1
Merchant Auto	1
Merchant Bulk	1
Merchant Chemical	1
Merchant Coastal	0.5
Merchant Container	1
Merchant Crude	1
Merchant Ferry	0.5
Merchant Gasoline	1
Merchant General	1
Merchant Liquified Gas	1
Merchant Molasses	1
Merchant Ore	1
Merchant Ore/Bulk/Oil	1
Merchant Passenger	1
Merchant Reefer	1
Merchant RO/RO	1
Merchant Super Tanker	3
Merchant ULCC	3
Merchant VLCC	3
Tugs, Ocean	0.5
Warship - General	1
Warship Surface	1

A following sample calculation demonstrates the method to estimate total manoeuvring distance for a vessel calling on a typical port:

Vessel Class: Merchant Tanker

Inbound Distance + Outbound Distance = Total Manoeuvring Distance (3)

Total Manoeuvring Distance= 1 + 1 = 2 nautical miles

For larger ports in the study area that have a number of terminals within a port boundary, an average total port manoeuvring distance was estimated based on factors including the total length of the port, harbour pilot service trip distances, and harbour tug trip distances. The approximate mid-point of the length of the port area was adopted to minimize the error in the total transit distance for vessels bound for port/terminal locations from different entry points. Intra-port manoeuvring distances are listed in Table 2-14.

Table 2-14 Intraport Manoeuvring Distance

Major Port	Region	Intraport Manoeuvring Distance (nautical miles)
Thunder Bay	5	3.50
Détroit	7	11.50
Détroit Red River	7	2.50
Sarnia	7	5.85
Windsor	7	11.50
Nanticoke	8	2.00
Welland Canal wharf	8	22.51
Wyandotte	8	3.53
Hamilton	9	5.00
Montréal	10	10.00
Ste Anne de Bellevue	10	10.00
Cacouna	11	2.00
Port Alfred	11	2.00
Québec	11	5.00
Sorel	11	2.00
Tadoussac	11	0.80
Trois-Rivières	11	5.00
Baie Comeau	12	1.50
Les Méchins	12	1.50
Matane	12	2.00
Port Cartier	12	2.00
Sept-Iles	12	6.00
Darmouth	16	4.50
Halifax	16	4.50
Strait of Canso,Pirate	16	5.00
St-John	17	1.50
Corner Brook	18	11.00

A sample calculation demonstrates the method to estimate total manoeuvring distance for a vessel calling on a major port:

Merchant Tanker vessel calling on the Port of Montréal:

Total Manoeuvring Distance = Inbound Trip + Outbound Trip (4)

= (Inbound + ½ Intraport) + (½ Intraport + Outbound)

= 1 + ½(10) + ½(10) + 1 = 12 nautical miles

2.3.6 Ship Hotelling Times at Dock or Anchor in Domestic Ports

Ship hotelling times at dock or anchor in domestic ports were estimated in the following manner. Using the INNAV data for 2003, all recorded trips for vessels of 500 gross tons (GT) and greater were extracted. This data was then sorted first by vessel name (code) and then by date and time

of arrival at port or anchor. A query was then applied to verify for each trip by each vessel, if the origin of the following trip was the same as the destination of the previous trip. When the result was true, the duration between the arrival of the first trip and the departure of the following trip was calculated. An average hotelling time was thus obtained for every port, terminal and anchor point. The sample of hotelling times is based on over 38,000 records. Significant outliers were removed and the final results are summarized in the Table 2-15, along with typical values estimated for other North American ports:

Table 2-15 Average Hotelling Times

Vessel Class	Hotelling Time (hours)			
	INNAV (This Study)	Port of Los Angeles (Starcrest)	Port of Cleveland (EPA)	Burns Waterway (EPA)
Merchant (Dry)	3.9			
Merchant (Tanker)	37.9	30.16	29	
Merchant Auto	10.0	17.35		
Merchant Bulk	59.4	72.16	60.0,7.4 (S,L)	45.8,16.6 (S,L)
Merchant Chemical	33.2			
Merchant Coastal	47.7			
Merchant Container	38.4	42.8	68.1	
Merchant Crude	35.2			
Merchant Ferry	1.0*			
Merchant Gasoline	27.3			
Merchant General	57.2	39.83	64.6	26
Merchant Liquified Gas	54.7			
Merchant Molasses	55.4			
Merchant Ore	27.9			
Merchant Ore/Bulk/Oil	77.0			
Merchant Passenger	40.5			
Merchant Reefer	56.2	29		
Merchant RO/RO	44.2	43.66		
Merchant Super Tanker	37.4	30.16	29	
Merchant ULCC	33.0	30.16	29	
Merchant VLCC	45.2	30.16	29	
Tugs, Ocean	64.1	41.5		
Warship - General	71.8			
Warship Surface	48.5			

Note: S=Salty, L=Laker

* Nominal value based on ferry schedules and number of trips per day.

2.4 Spatial Disaggregation of Emissions

2.4.1 Percent of Transit Emissions in Regions

The percentage of underway emissions in each region is based on the distance in every region traversed during the selected movement. The distance travelled in each region is expressed as a percentage of the total port-to-port route distance.

2.4.2 Assignment of Manoeuvring and Hotelling Emissions to Regions

Hotelling emissions occur within the port boundary and are assigned to the region that the port is located in. It is assumed that all manoeuvring emissions also occur within the port boundary, therefore, the emissions are also allocated to the arrival port's region.

2.5 Overview of Changes to the Previous Version of the Marine Vessel Emission Inventory Tool

In August 2005, Levelton completed a project to develop a commercial marine vessel emission inventory tool and data system for Environment Canada's use in compiling a national marine emission inventory. The application was developed in Microsoft Access to generate emission estimates using a bottom-up methodology based on Lloyd's port-to-port activity data for vessels operating on Canadian waters. The earlier application was the starting point for the emission inventory system developed in this study with the following subsequent modifications:

- The Lloyds data utilizes a general and sub-type vessel classification system. The general vessel type code was used as the link to the appropriate emission factor, load factor, default speeds, etc. In the INNAV data set, the general vessel types covered a broad range of vessel categories and are too general to form a suitable link to the emission parameters. A change in the application was made to use the vessel sub-type for the look-up of the appropriate emission parameter.

- The location coding in the INNAV data makes use of a 3-digit area code to identify a port area and any terminals within a port. The area code was used as the port location code in the database for assigning ports to regions and for coding route end points.

- A method was developed to calculate the upper and lower estimates of emissions based on estimates of uncertainty in the emission factors and the vessel activity data. Modifications to the emission tool were programmed to calculate the lower and upper emission values for each vessel type based on input values stored on the percent uncertainty in emission factors and vessel activity. Calculation of these emission values is automated in the tool so the user can revise inputs and update the uncertainty estimates.

- As discussed in the description of the methodology in Section 2.2, a review of current methods and assumptions for estimating marine vessel emissions was conducted. The researched parameters were imported into the appropriate look-up tables in the emission tool including: 'EmissionFactors', 'LoadFactors', 'Speeds', 'AuxEnginePower'.

- Programming was added to enable generation of spatially gridded emission results for each region using a format suitable for input to regional air quality dispersion models.

3. BASELINE MARINE EMISSION INVENTORY FOR 2002

Emission inventory results presented in this section were extracted from the reporting module in the emission tool. These final results were reviewed and checked by conducting manual inspections of the data, cross-checking sums from the data base to the report and manually checking emission calculations for individual vessels selected at random from the INNAV dataset.

The reports are generated in spreadsheet format with pick-list filters that allow the user to view the inventory at selectively finer levels of detail. The Marine Emission Inventory Tool can generate additional reports other than those included in this report simply by manipulating the pivot table filters.

3.1 TOTAL BASE YEAR EMISSIONS

A screen shot of the reporting window is presented in Table 3-1 to demonstrate the layout and filter options:

Table 3-1 Main Pivot Table Report Screen and 2002 Inventory Summary

Microsoft Excel - Worksheet in Report 1 - Base Year Emissions : Form

File Edit View Insert Format Tools Data Window Help Adobe PDF

PivotTable

E8

	A	B	C	D	E	F	G
1	**Marine Vessel Base Year Emissions (tonnes)**						
2							
3	Vessel Type	(All)					
4	Vessel Sub-Type	(All)					
5	Mode	(All)					
6	Port	(All)					
7	Region	(All)					
8	Province	(All)					
9	Month	(All)					
10	Domestic	(All)					
11	Canada/USA	(All)					
12	International	(All)					
13							
14	Emissions						
15	Name	Total					
16	CO2	3,298,991.8					
17	NOx	93,699.5					
18	SO2	47,459.0					
19	VOC	2,843.2					
20	CO	3,092.9					
21	TPM	10,348.4					
22	PM10	8,157.0					
23	PM25	6,854.8					
24	HC	2,843.2					

3.2 Emissions by Operating Mode

The predominant source of emissions from marine vessels is the main engine while the vessel is underway, as illustrated by the summary of emissions by mode of operation presented in Table 3-2. Although smaller than underway emissions, hotelling and manoeuvring emissions could be significant in port areas compared to other sources.

Table 3-2 Emissions in 2002 by Operating Mode

Substance	Underway (tonnes/year)	Hotelling (tonnes/year)	Manoeuvring (tonnes/year)	Total (tonnes/year)
CO_2	2,924,988.4	346,731.3	27,272.0	3,298,991.8
NOx	86,161.4	7,024.7	513.5	93,699.5
SO_2	42,896.5	4,303.9	258.6	47,459.0
VOC	2,619.9	194.5	28.8	2,843.2
HC	2,619.9	194.5	28.8	2,843.2
CO	2,605.1	437.7	50.1	3,092.9
TPM	9,741.3	562.9	44.1	10,348.4
PM_{10}	7,650.9	469.8	36.3	8,157.0
$PM_{2.5}$	6,400.6	423.2	30.9	6,854.8

3.3 Emissions by Vessel Class

As shown in Figure 3-1, bulk carrier, container and tanker vessels were consistently the three largest contributors to emissions of carbon dioxide and the primary pollutants of concern in regard to effects on air quality in the 2002-2003 base year. The combined contribution from this group of vessels ranges from 67% to 74% for these four contaminants.

A detailed breakdown of base year emissions by pollutant and type of vessel is provided in Table 3-3.

3.4 Emissions by Region in Canadian Waters

Table 3-4 summarizes base year emissions for the regions defined for the emission inventory.

3.5 Emissions by Month

Table 3-5 summarizes the base year emissions from allclasses of vessels my month of the year based on the times recorded in the INNAV database for vessel movements. Emissions are lowest in January through March and remain near their highest levels in May, July, August, September and October. The months when minimum or maximum values occur are not the same for all pollutants.

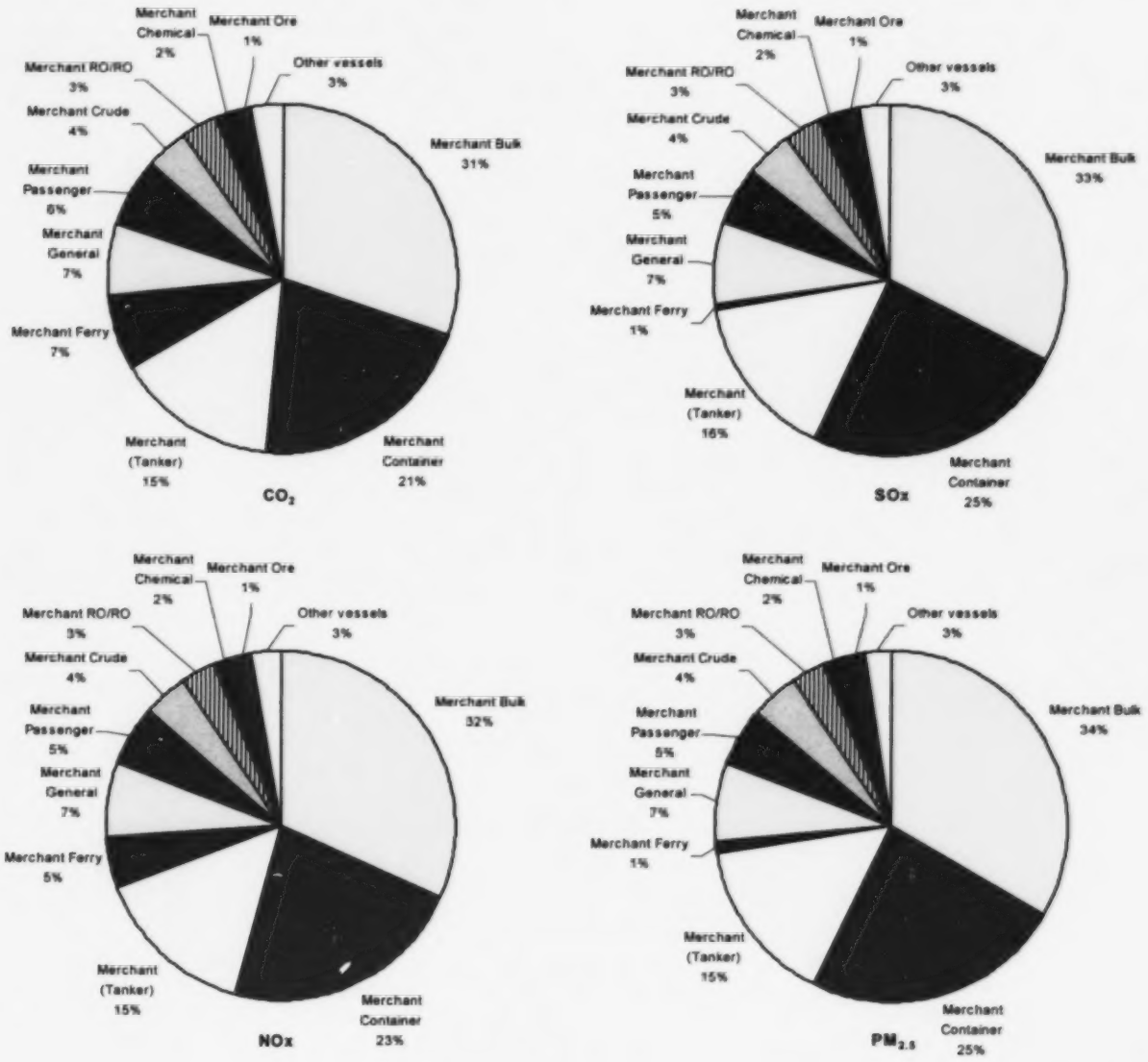

Figure 3-1 Distribution of 2002 CO_2, SOx, NOx and $PM_{2.5}$ Emissions by Class of Vessel

Table 3-3 Emissions in 2002 by Class of Vessel

Vessel Class	Annual Emissions (tonnes/year)								
	CO_2	NOx	SO_2	VOC	HC	CO	TPM	PM_{10}	$PM_{2.5}$
Merchant (Dry)	149.2	4.5	2.5	0.1	0.1	0.1	0.5	0.4	0.4
Merchant (Tanker)	489,910.5	13,954.2	7,276.9	430.1	430.1	443.4	1,591.5	1,254.7	1,055.6
Merchant Auto	12,236.4	369.4	198.6	11.6	11.6	10.2	43.8	34.3	28.6
Merchant Bulk	996,218.1	29,616.4	15,412.5	923.3	923.3	847.8	3,474.7	2,728.0	2,282.4
Merchant Chemical	70,822.8	2,046.1	1,149.7	63.4	63.4	62.9	235.7	185.5	155.8
Merchant Coastal	1,930.4	56.1	26.5	1.7	1.7	1.7	6.5	5.1	4.3
Merchant Container	703,610.2	21,121.8	11,611.7	658.0	658.0	589.6	2,491.6	1,954.5	1,633.5
Merchant Crude	134,840.5	3,964.4	2,074.8	122.9	122.9	116.6	461.5	362.7	303.9
Merchant Ferry	233,089.7	4,585.2	250.1	86.0	86.0	389.6	71.2	71.2	71.2
Merchant Gasoline	1,417.4	41.6	23.6	1.3	1.3	1.2	4.8	3.8	3.2
Merchant General	219,190.6	6,493.5	3,527.1	201.7	201.7	187.4	759.7	596.6	499.5
Merchant Liquified Gas	629.1	17.4	8.6	0.5	0.5	0.6	1.9	1.5	1.3
Merchant Molasses	841.2	24.1	13.9	0.7	0.7	0.8	2.8	2.2	1.8
Merchant Ore	42,485.1	1,281.0	661.6	40.0	40.0	35.4	151.6	118.8	99.3
Merchant Ore/Bulk/Oil	21,652.0	590.0	342.8	18.0	18.0	20.8	65.2	51.7	43.7
Merchant Passenger	205,108.8	5,091.7	2,498.2	151.7	151.7	218.4	523.0	419.3	360.2
Merchant Reefer	6,907.8	206.8	116.0	6.4	6.4	5.8	24.3	19.1	16.0
Merchant RO/RO	104,544.7	2,879.0	1,630.5	88.1	88.1	98.9	320.8	253.8	214.5
Merchant Super Tanker	7,870.8	228.5	130.5	7.1	7.1	6.9	26.4	20.8	17.4
Merchant ULCC	1,849.9	52.4	30.4	1.6	1.6	1.7	6.0	4.7	4.0
Merchant VLCC	23,822.0	681.1	392.4	21.0	21.0	21.5	77.9	61.4	51.6
Tugs Ocean	19,569.1	385.7	79.6	7.6	7.6	31.4	6.0	6.0	6.0
Warship - General	81.8	2.5	0.1	0.1	0.1	0.1	0.3	0.2	0.2
Warship Surface	213.9	6.3	0.3	0.2	0.2	0.2	0.7	0.6	0.5
All Vessels	3,298,991.8	93,699.5	47,459.0	2,843.2	2,843.2	3,092.9	10,348.4	8,157.0	6,854.8

Table 3-4 Emissions in 2002 by Region – Canadian Waters

	Region	Annual Emissions (tonnes/year)								
		CO_2	NOx	SO_2	VOC	HC	CO	TPM	PM_{10}	$PM_{2.5}$
5	Lake Superior	68,762.0	2,053.3	1,063.4	63.9	63.9	58.2	241.2	189.3	158.3
6	Lake Huron/Georgian Bay	126,731.0	3,780.1	1,953.4	117.3	117.3	107.5	443.1	347.8	290.9
7	Lake St. Clair	55,666.8	1,500.4	820.1	47.0	47.0	54.4	165.4	131.1	111.0
8	Lake Erie	104,068.8	3,083.6	1,603.3	95.9	95.9	89.2	360.3	283.0	236.8
9	Lake Ontario	128,245.2	3,775.1	1,977.6	117.3	117.3	110.8	439.9	345.7	289.6
10	St. Lawrence Seaway	79,418.4	2,000.6	1,136.4	62.2	62.2	83.8	209.9	167.8	143.5
11	St. Lawrence River	374,445.1	10,138.4	4,740.3	297.9	297.9	389.6	1,026.2	812.6	685.9
12	Mouth of St. Lawrence River	303,523.0	8,927.2	4,646.6	275.8	275.8	265.3	1,030.5	809.7	678.1
13	Gulf of St. Lawrence (Quebec Region)	189,441.0	5,716.6	3,000.4	177.8	177.8	157.5	675.7	529.8	442.6
14	PEI	19,055.1	404.6	122.4	10.0	10.0	27.2	23.3	19.5	17.4
15	Gulf of St. Lawrence (New Brunswick)	28,400.0	781.4	405.3	23.8	23.8	27.0	86.6	68.5	57.9
16	Nova Scotia (North and Eastern side)	866,195.7	24,521.5	12,406.6	740.8	740.8	818.7	2,688.7	2,120.0	1,782.0
17	Bay of Fundy	108,541.5	2,864.7	1,510.5	85.8	85.8	110.1	302.8	240.7	204.6
18	Western Newfoundland	158,807.8	4,430.4	2,140.2	131.5	131.5	157.2	467.2	368.8	310.2
19	East Shore of Newfoundland	654,008.5	18,803.9	9,455.6	568.5	568.5	604.1	2,086.3	1,642.5	1,378.1
20	North Shore of Newfoundland/Labrador	33,681.9	917.7	476.8	27.9	27.9	32.3	101.2	80.2	67.9
	All Regions	3,298,991.8	93,699.5	47,459.0	2,843.2	2,843.2	3,092.9	10,348.4	8,157.0	6,854.8

Table 3-5 Emissions in 2002 by Month

Month	Annual Emissions (tonnes/year)								
	CO_2	NOx	SO_2	VOC	HC	CO	TPM	PM_{10}	$PM_{2.5}$
January	190,006.6	5,431.1	2,766.4	164.7	164.7	177.1	600.8	473.2	397.3
February	169,414.4	4,840.0	2,471.9	146.8	146.8	158.0	535.4	421.7	354.1
March	192,768.8	5,485.2	2,814.8	166.4	166.4	180.4	606.1	477.6	401.3
April	250,172.8	7,187.3	3,677.8	219.1	219.1	230.3	802.6	631.9	530.3
May	309,620.5	8,897.7	4,542.7	271.4	271.4	284.5	995.5	783.8	657.8
June	277,596.7	7,791.2	3,904.1	235.2	235.2	265.9	847.9	669.2	563.1
July	339,466.3	9,494.3	4,728.9	285.8	285.8	326.9	1,029.1	812.4	684.0
August	328,591.8	9,241.7	4,610.7	278.5	278.5	314.3	1,005.4	793.3	667.3
September	326,856.8	9,105.2	4,554.4	274.7	274.7	314.7	989.7	781.7	658.7
October	338,437.4	9,581.8	4,855.4	291.5	291.5	316.6	1,062.8	838.1	704.8
November	297,589.8	8,599.6	4,415.4	263.2	263.2	270.4	968.9	762.5	639.5
December	278,469.8	8,044.5	4,116.6	245.8	245.8	253.7	904.2	711.5	596.7
Total	3,298,991.8	93,699.5	47,459.0	2,843.2	2,843.2	3,092.9	10,348.4	8,157.0	6,854.8

4. UNCERTAINTY ANALYSIS

Uncertainty in emission inventories is often of high interest to users of emission inventory data, but difficult to determine reliably. Uncertainty in calculated emissions arises for vessels in underway, manoeuvring and hotelling modes of activity from uncertainty in the estimates of both energy use and emission factors. This is illustrated in the following general form of the equation used to calculate emissions (E) by mode and pollutant with uncertainty terms for energy use (U_E) and emission factor (U_{EF}):

$$E_{mode,\ pollutant} = (\text{Vessel Annual Energy Use} +/- U_E) \times (\text{Emission Factor} +/- U_{EF}) \quad (5)$$

This inventory utilized the best available information on the characteristics of the engines and routes travelled by marine vessels in the study to provide a reliable estimate of emissions. However, the simplifying assumptions and approximations that had to be applied to develop estimates of vessel energy use during each vessel movement, and in total, contribute some level of uncertainty to the calculated emissions. To the knowledge of the authors, the uncertainty in estimates of the vessel energy use developed by applying the methods adopted in this study has not been evaluated though any systematic or random comparison of estimates with actual vessel energy use. Consequently, the uncertainty in vessel energy use by mode of activity can only be estimated using professional judgement. This approach was used to develop the estimates of uncertainty in energy use shown in Table 4-1.

The uncertainty in emission factors for ocean-going vessels has been evaluated by Entec (2002), SMED (2004) and Corbett and Koehler (2003). The mid-points of the ranges of uncertainty determined by SMED for each pollutant and mode of vessel operation at a 95% confidence level were used in this study, as summarized in Table 4-1.

Table 4-1 Uncertainty Estimates for Emission Factors and Vessel Energy Use

Vessel Class	Pollutant CAS Number	Vessel Mode	Emission Factor Uncertainty	Vessel Energy Use Uncertainty
All	11104-93-1	manoeuvring	35%	50%
All	11104-93-1	port	15%	30%
All	11104-93-1	underway	8%	15%
All	124-38-9	manoeuvring	15%	50%
All	124-38-9	port	8%	30%
All	124-38-9	underway	8%	15%
All	630-08-0	manoeuvring	35%	50%
All	630-08-0	port	15%	30%
All	630-08-0	underway	15%	15%
All	7446-09-5	manoeuvring	35%	50%
All	7446-09-5	port	35%	30%
All	7446-09-5	underway	35%	15%
All	NA - M08	manoeuvring	50%	50%
All	NA - M08	port	35%	30%
All	NA - M08	underway	35%	15%
All	NA - M09	manoeuvring	50%	50%
All	NA - M09	port	50%	30%
All	NA - M09	underway	50%	15%
All	NA - M10	manoeuvring	50%	50%

Vessel Class	Pollutant CAS Number	Vessel Mode	Emission Factor Uncertainty	Vessel Energy Use Uncertainty
All	NA - M10	port	50%	30%
All	NA - M10	underway	50%	15%
All	NA - M16	manoeuvring	35%	50%
All	NA - M16	port	35%	30%
All	NA - M16	underway	15%	15%
All	NA - M16b	manoeuvring	35%	50%
All	NA - M16b	port	35%	30%
All	NA - M16b	underway	15%	15%

Uncertainties in emissions relative to the best estimate were determined using a simplified method recommended by the International Panel on Climate Change for analysis of uncertainty in estimates of greenhouse gas emissions. This method applies standard statistical formulas to determine the combined uncertainty when summing and multiplying uncertainty terms. Use of these formulas is illustrated below:

a) **Uncertainty for multiplication of terms**: Given a function P = A x B,

The uncertainty in P is U_p = Square Root ($U_a^2 + U_b^2$) (6)

b) **Uncertainty for addition of terms**: Given a function S = A + B,

The uncertainty in S is U_s = Square Root ($(U_a x A)^2 + (U_b x B)^2$) (7)

The steps used to calculate uncertainty in the base emission inventory were as follows:

1. Sum best-estimate emissions of each pollutant from all vessels for each mode of activity.
2. Determine the combined uncertainty in percent for each pollutant when multiplying uncertainties in energy use and emission factors by using Equation a) above.
3. Multiply the combined uncertainty in Step 2 by the sum of best-estimate emissions for the corresponding pollutant and mode of activity and then add and subtract this value from the best estimate to determine upper and lower bounds of emissions for each pollutant by mode of activity.
4. Determine the combined uncertainty in percent for each pollutant when summing emissions by mode of activity by using Equation b) above and the uncertainties by mode determined in Step 2.
5. Multiply the combined uncertainties in Step 4 by the sum of emissions for each pollutant by mode of activity and then add and subtract this value from the best estimate to determine overall upper and lower bounds of emissions for each pollutant.

The estimated upper and lower bounds for the emission inventory using the method described above are presented in Table 4-2.

Table 4-2 Upper Bound, Best Estimate and Lower Bound of Emissions in 2002

Substance	Emissions (tonnes/year)			Uncertainty in Best Estimate (%)
	Lower Bound	Best Estimate	Upper Bound	
CO_2	2,796,673.2	3,298,991.8	3,801,310.4	15.2%
NOx	79,055.6	93,699.5	108,343.4	15.6%
SO_2	31,003.7	47,459.0	63,914.3	34.7%
VOC	2,280.0	2,843.2	3,406.4	19.8%
HC	2,280.0	2,843.2	3,406.4	19.8%
CO	2,520.3	3,092.9	3,665.5	18.5%
TPM	6,629.8	10,348.4	14,066.9	35.9%
PM_{10}	4,153.6	8,157.0	12,160.3	49.1%
$PM_{2.5}$	3,504.4	6,854.8	10,205.2	48.9%

5. EMISSION FORECASTS

5.1 GENERAL METHODOLOGY

Forecasts are estimated based on application of factors to simulate the effect of growth in vessel activity level, changes in the emission characteristics of vessels, and application of emission controls to vessel emission sources. Multiple growth/control scenarios can be stored and identified by a unique ID in one of the three scenario categories:

'ScenarioGrowth' - Growth ratio relative to base year. This simulates the anticipated future change in the underlying activity level of the source category based on trends in a surrogate parameter. A value of 1 indicates no change, while values of more than 1 indicate an increase.

'ScenarioBusinessAsUsual' - Ratio of uncontrolled emissions in a future year relative to the base year. This simulates the business as usual (BAU) case and simulates the change in emissions that are expected to occur due to existing legislation or voluntary improvements in technology or fuels without implementation of new emission controls.

'ScenarioControl' - Ratio of future control level relative to the base year. This simulates the change in emissions resulting by implementing additional emission control measures. This level of control is additional to that resulting from the change in the emission characteristics of the sources that would otherwise occur.

The 'Scenarios' table is used to select the combination of growth scenarios that apply to a vessel category, substance, and region. The database table relationships are summarized in Figure 5-1:

$$Forecast = base\ emission \times growth\ factor \times BAU\ factor \times control\ factor \quad (8)$$

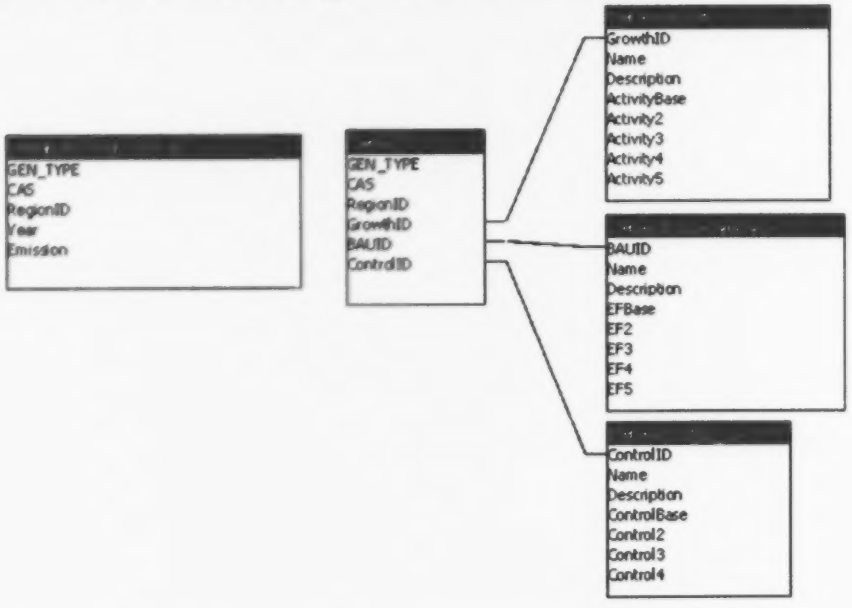

Figure 5-1 Structure of Tables in Marine Tool for Forecasting Emissions

This design was chosen as it allows flexibility in establishing forecast scenarios. For example, to forecast emissions based on future sulphur level changes in fuels, an activity growth profile can be entered or selected from the 'ScenarioGrowth' table, a profile can be set up in the 'ScenarioBusinessAsUsual' table to model the future changes in emissions resulting from sulphur reductions, and the 'ScenarioControl' table can be used to model effects of emission controls. In the 'Scenarios' table, any combination of these three profiles can be assigned to a pollutant, by region (to account for variations amongst the regions), and by general vessel class.

5.2 GROWTH FACTORS

A survey was conducted to develop information that could be used to forecast vessel traffic in the study area, which involved contacting staff at all the main marine ports in Eastern Canada, staff with Surface and Marine Statistics and Forecast at Transport Canada, and specialists at the University of BC, University of Montreal and Concordia University who undertake research in related fields of study. Staff with the following Port Authorities was contacted to request available forecasts of vessel traffic for 2010 and 2020 that could be used in the study:

- Halifax;
- Montreal;
- Saint John;
- St. John's;
- Sault Ste Marie;
- Thunder Bay;
- Toronto; and
- Hamilton.

No forecast statistics were available from any of the Port Authorities contacted. The ports of Sault Ste Marie, Saint John and Halifax responded with general information indicating only the likelihood of port cargo throughput increasing or decreasing in the next few years.

The most complete data suitable for forecasting changes by 2010 and 2020 in the tonnage of cargo transported by ocean-going marine vessels was available from Transport Canada (Kochhar, 2006). This data applies to national marine cargo shipments and was obtained and used as a surrogate for future changes in the emissions from ocean-going vessels on the Great Lakes and on the Eastern seaboard. Emissions will change as a result of the combined effects of changes in the number of vessels operating in the study area and in the average power rating of main and auxiliary engines on these vessels.

Growth factors were developed to approximate the change in emissions for each vessel type relative to emissions in 2002. The surrogate for growth in emissions is tonnage of commodities transported on each type of vessel in the INNAV dataset. The growth factors were developed using national data provided by Transport Canada on the tonnage of commodities shipped in 2002 by type of vessel, and the tonnes per year of each commodity forecast to be shipped through Canadian ports in 2010 and 2020. The forecast includes both domestic and international shipments. The steps in the analysis to develop the growth factors were as follows:

1. For 2002, determine the tonnage and fraction of total tonnage of each commodity transported on each class of vessel in the INNAV dataset, including all the major classes of vessels;

2. For each class of vessel, apply the mass fractions of commodities transported by ship in 2002 developed in Step 1 to the total tonnes per year of commodities forecast to be transported by ship in 2010 and 2020.

3. For each class of vessel, sum the tonnes per year of each commodity to estimate the total tonnes of all commodities forecast to be shipped in 2010 and 2020.

4. For each class of vessel, calculate the growth fractions as the ratio of tonnes per year forecast to be shipped in 2010 and 2020 determined in Step 3 by the base quantity shipped in 2002 determined in Step 1.

Step 1 in the analysis included 91% of the total of all commodities shipped domestically and internationally in 2002. The vessels carrying the balance of the commodities shipped were typically sub-types of the vessel class included, were outside the scope of work, or represented less than 1% of commodities shipped. Some vessel classes in the INNAV dataset were not represented in the base year commodity shipment statistics compiled by Transport Canada and growth fractions for these classes of vessels were estimated from results for the most similar vessel class.

The data provided by Transport Canada itemize commodity shipments by vessel class in 2002. The aggregate amounts for all commodities by vessel class are presented in Table 5-1. Non-containerized commodities comprise 92.4% of total commodity shipments. The vessel class included in the forecast analysis are also indicated in this table and were selected if they were a vessel class in the INNAV dataset and amounted to about 1% or more of the total commodities shipped. Some of the vessel types shown in the table are subsets of the more broadly defined vessel types used by INNAV, and these were grouped accordingly.

National commodity movements by marine vessel for the base year and forecasts for 2010 and 2020 provided by Transport Canada are presented in Table 5-2. Overall, commodity shipments are forecast to increase 11% by 2010 and 21% by 2020.

The growth factors developed from the commodity forecasts for major vessel classes are listed in Table 5-3. Growth factors for the balance of the INNAV vessel classes not included specifically in the commodity forecast were estimated by using growth factors for similar vessels. These vessel classes, the vessel classes they were assumed to be similar to, and the corresponding growth factors are listed in Table 5-4. No data was available on growth in movements of ferries or military vessels and emissions were assumed to remain constant for these vessel classes.

Table 5-1 2002 Commodity Marine Shipments by Vessel Class

Vessel Class	Non container (tonnes/year)	%	Container (tonnes/year)	%	Total (tonnes/year)	%	Included in Forecast Analysis
Bulk Carrier	50,980,590	15.97	2,435	0.01	50,983,025	14.76	Yes
Bulk Oil Carrier	184,466	0.06		0.00	184,466	0.05	No
Bulk/container Carrier	1,065,440	0.33	26,815	0.10	1,092,255	0.32	No
Chemical Tanker	3,562,217	1.12		0.00	3,562,217	1.03	Yes
Container	797,968	0.25	24,231,613	92.96	25,029,581	7.25	Yes
Crude Oil Tanker	33,890,186	10.61		0.00	33,890,186	9.81	Yes
Crude/products Tanker	12,579,711	3.94		0.00	12,579,711	3.64	Yes
Cruise	1,611	0.00		0.00	1,611	0.00	No
Dry Cargo Barge	25,366,188	7.94	140	0.00	25,366,327	7.34	No
Fish Processing And Catching	15,360	0.00		0.00	15,360	0.00	No
General Cargo	2,206,583	0.69	27,978	0.11	2,234,561	0.65	Yes
General Cargo/container	9,216	0.00	8,059	0.03	17,275	0.01	No
General Cargo/multi Deck	845,454	0.26	58,702	0.23	904,156	0.26	No
General Cargo/single Deck	5,770,001	1.81	385,414	1.48	6,155,416	1.78	Yes
Livestock Carrier	478	0.00		0.00	478	0.00	No
Lpg Carrier	291,777	0.09		0.00	291,777	0.08	Yes
Offshore Production And Support	82,674	0.03		0.00	82,674	0.02	No
Offshore Support	209,726	0.07	64	0.00	209,790	0.06	No
Oil Products Tanker	9,590,050	3.00		0.00	9,590,050	2.78	Yes
Oil Tanker	27,473,288	8.60		0.00	27,473,288	7.95	Yes
Oil/chemical Tanker	5,655,673	1.77		0.00	5,655,673	1.64	Yes
Ore Carrier	1,944,904	0.61		0.00	1,944,904	0.56	Yes
Ore/Bulk/Oil	2,224,004	0.70	6	0.00	2,224,010	0.64	Yes
Ore/oil	280,255	0.09		0.00	280,255	0.08	No
Other Bulk Carrier	127,882,100	40.05	4,164	0.02	127,886,264	37.03	Yes
Other Nei	1,888	0.00		0.00	1,888	0.00	No
Other Ro-Ro Cargo	1,444,190	0.45	263,346	1.01	1,707,537	0.49	Yes
Other Specialised Carrier	686,456	0.21	3,501	0.01	689,957	0.20	No
Reefer	66,126	0.02		0.00	66,126	0.02	Yes
Ro-Ro Passenger	820	0.00		0.00	820	0.00	No
Specialised Carrier	444,333	0.14	408,381	1.57	852,714	0.25	No
Tug	2,824,623	0.88	19,427	0.07	2,844,050	0.82	Yes
Vehicle Carrier	915,019	0.29	627,276	2.41	1,542,295	0.45	Yes
Grand Total	319,293,375		26,067,320		345,360,696		

Table 5-2 Base Year and Forecast Marine Shipments by Commodity Type

Commodity	2002	2010	2020
Alcoholic and Non-Alcoholic Beverages	195,851	110,696	110,011
Animal Feed and Products	308,767	857,902	849,346
Articles of Base Metal	745,618	814,977	839,724
Autos and Other Equipment	557,451	640,668	728,275
Basic Chemicals	10,556,533	11,117,695	11,997,455
Canola	2,212,557	3,777,844	4,050,107
Cement	4,564,504	4,770,411	5,107,033
Coal	47,597,278	52,212,107	54,130,585
Containerized	26,067,315	33,504,469	45,298,953
Crude Petroleum	59,021,279	62,639,468	65,152,939
Electronic, Electrical Equipment and Office Equipment	140,845	166,652	167,000
Fertilizers	1,087,186	1,120,807	1,120,877
Fuel Oils	14,373,017	15,944,657	17,203,944
Gasoline and Aviation Turbine Fuel	16,358,518	16,673,390	17,848,208
Gypsum	7,797,812	8,396,789	8,948,229
Iron and Steel - Primary and Semi-Finished	3,605,232	3,919,989	4,166,277
Iron Ore and Concentrates	37,701,927	42,464,776	46,617,712
Live Animals	3,529	3,118	3,127
Logs and Other Wood In The Rough	7,272,632	7,947,022	9,459,304
Liquefied petroleum gases and Other Refined Petroleum & Coal Products	6,342,756	5,334,679	5,313,982
Lumber	2,057,044	2,375,743	2,378,340
Machinery	138,295	161,455	190,602
Meat, Fish, Seafood	613,827	250,256	251,163
Mixed Loads or Unidentified Freight or Cargo	420,193	395,909	396,456
Newsprint	3,127,534	3,190,834	3,281,491
Non-Ferrous Metals - Primary and Semi-Finished	646,725	682,303	699,438
Other Agriculture Products	4,150,351	5,613,448	6,659,407
Other Cereal Grains	1,772,748	2,610,978	2,660,221
Other Chemical Products & Preparations	53,840	43,640	43,149
Other Manufactured and Miscellaneous Goods	44,103	47,472	47,486
Other Metallic Ores and Concentrates	8,087,073	9,309,345	9,973,590
Other Non-Metallic Mineral Products	1,039,701	548,992	547,473
Other Non-Metallic Minerals	3,248,924	2,703,440	2,731,960
Other Wood Products (Plywood, Veneer, Etc)	178,424	161,526	161,920
Paper and Paperboard	303,780	387,104	386,786
Parts and Accessories For Motor Vehicles	518	416	415
Plastic and Rubber Products	49,004	43,268	42,877
Potash	5,178,559	4,886,798	4,893,760
Prepared Foods	2,170,394	2,460,984	2,668,566
Salt	8,050,958	8,565,341	8,964,670
Stone, Sand, Gravel and Crushed Stone	20,526,641	21,838,566	23,554,109
Sulphur	5,217,110	5,408,023	5,972,928
Waste and Scrap	3,585,277	3,720,654	4,215,807
Wheat	14,562,642	20,120,264	21,353,805
Wood Chips	8,415,545	9,259,217	9,888,919
Wood Pulp	5,210,874	5,743,104	6,567,049
Total	345,360,691	382,947,196	417,645,476
Growth factor	1	1.11	1.21

Table 5-3 Growth Factors for Vessel Classes Included in Commodity Forecast

INNAV Vessel Class	Transport Canada Vessel Class	Growth Factors Relative to 2002			Annual Compounded Growth Rate (%)	
		2002	2010	2020	2002-2010	2010-2020
Merchant Bulk	Bulk Carrier + Other Bulk Carrier	1.00	1.11	1.18	1.3	0.6
Merchant Chemical	Chemical Tanker	1.00	1.06	1.14	0.7	0.7
Merchant Container	Container Vessel (total containerized)	1.00	1.29	1.74	3.2	3.1
Merchant Crude	Crude Oil Tanker	1.00	1.06	1.11	0.8	0.4
Merchant Tanker	Crude/products + Oil/Chemical Tanker	1.00	1.05	1.11	0.6	0.6
Merchant General	General Cargo + General Single-Deck Vessels	1.00	1.12	1.22	1.4	0.9
Merchant LG	Lpg Carrier	1.00	1.02	1.08	0.3	0.6
Merchant Tanker II	OIL Products Tanker + Oil Tanker	1.00	1.06	1.11	0.7	0.4
Merchant Ore	Ore Carrier	1.00	1.14	1.22	1.6	0.7
Merchant Ore/Bulk/Oil	Ore/Bulk/Oil Vessel	1.00	1.06	1.11	0.7	0.5
Merchant Ro/Ro	Other Ro-Ro Cargo	1.00	1.06	1.14	0.7	0.7
Merchant Reefer	Reefer	1.00	1.16	1.34	1.9	1.4
Tug Ocean	Ocean Tug	1.00	1.09	1.29	1.1	1.7
Merchant Auto	Vehicle Carrier	1.00	1.15	1.20	1.8	0.4
All Vessels	All Vessels	1.00	1.09	1.20	1.1	0.9

Table 5-4 Growth Factors for Vessel Classes Not Included in Commodity Forecast

INNAV Vessel Class	Similar INNAV Vessel Class Used	Growth Factors Relative to 2002			Annual Compounded Growth Rate (%)	
		2002	2010	2020	2002-2010	2010-2020
Merchant (Dry)	Merchant Bulk	1.00	1.11	1.18	1.3	0.6
Merchant Coastal	Merchant General	1.00	1.12	1.22	1.4	0.9
Merchant Ferry	None	1.00	1.00	1.00	0.0	0.0
Merchant Gasoline	Merchant Tanker	1.00	1.05	1.11	0.6	0.6
Merchant Molasses	Merchant Tanker	1.00	1.05	1.11	0.6	0.6
Merchant Passenger	None	1.00	1.00	1.00	0.0	0.0
Merchant Super Tanker	Merchant Crude	1.00	1.06	1.11	0.8	0.4
Merchant ULCC (Ultra Large Crude Carrier)	Merchant Crude	1.00	1.06	1.11	0.8	0.4
Merchant VLCC (Very Large Crude Carrier)	Merchant Crude	1.00	1.06	1.11	0.8	0.4
Warship General	None	1.00	1.00	1.00	0.0	0.0
Warship Surface	None	1.00	1.00	1.00	0.0	0.0

5.3 Factors for Estimating the Effects of Regulations on NOx, PM and SOx Emissions

Factors were developed to reflect the effect of the IMO NOx Limit for engines manufacture red in 2000 and later years and for the effect of Canadian regulations limiting the sulphur content of marine fuels sold domestically.

5.3.1 Forecast NOx Emission Factors

The IMO NOx emission limit for new engines manufactured starting in 2000 is illustrated in Figure 5-2. New engines normally achieve NOx emission levels that are below the IMO emission limits to ensure compliance. NOx emission limits typical of engines manufactured since 2000 are illustrated in Figure 5-2 by the chart values labelled as "Currently Achieved". A second scenario was considered in this study which assumed introduction of more stringent NOx emission limits equal to 75-78% of the current limits beginning with new or re-built engines made in 2012, or later. The nominal lower NOx emission limits of current commercial technology are also illustrated in Figure 5-2. NOx emission levels for current engines and the limits of current commercial technology were estimated from emission data reported by Wärtsilä for slow and medium speed engines (Schmid and Weisser, 2005; Heim, 2001 and Dogliani and Paro, 2004; Wärtsilä, 2006).

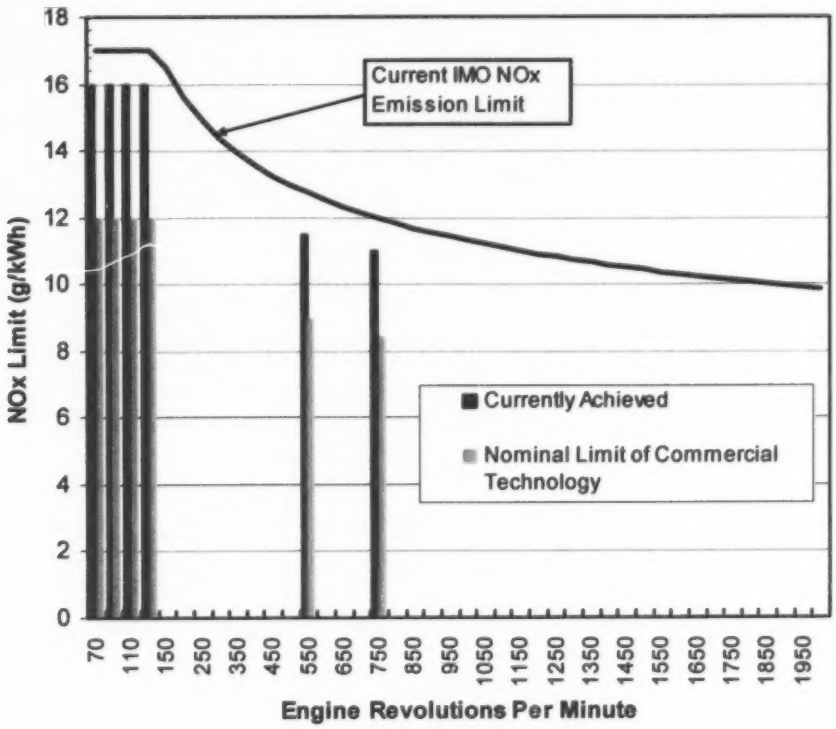

Figure 5-2 Forecast Scenarios for NOx Emission Limits for New Engines

The effect of gradual replacement of existing engines in the fleet with new engines meeting the current and future hypothetical IMO NOx emission limits was estimated using a simple model for turnover of this equipment. The assumptions for this model are as follows:

- Existing main and auxiliary engines are retired at an average rate of 2% per year and replaced by new engines meeting the assumed NOx emission limits;
- The proportion of slow speed and medium speed engines used for main engines remains constant as assumed for the base year (95% slow speed and 5% medium speed);
- The proportion of auxiliary engines using residual oil and marine diesel oil remains constant at the value assumed for the base year (75% residual oil and 25% marine diesel oil);
- NOx emission factors for the engines in the existing fleet remain constant at the same values used for the 2002 base year.

Table 5-5 shows the NOx emission factors estimated using the simple forecast model for the fleet in 2010 and 2020, and the corresponding percent reductions relative to the emission factors in 2002 for main and auxiliary engines. The percent reduction in the NOx emission factor for main engines during manoeuvring was assumed to be the same as calculated for the main engine underway. At a 2% replacement rate and with continuation of the current IMO NOx emission limit to 2020, the average NOx emission factor for the fleet will decrease 5.7% for main engines and 8.3% for auxiliary engines. A significantly greater reduction in NOx emissions would be achieved if the assumed, more stringent NOx emission limits are implemented by the IMO for new engines starting in 2012.

Table 5-5 Forecast Scenarios for Fleet Average NOx Emission Factors

a) Scenario A – Current technology and no future change to 2020 in NOx emission limit.						
Engine	New Engine			Forecast Fleet Average		
	Year	NOx (g/kWh)		Year	NOx (g/kWh)	Reduction from 2002
		RO	MDO			
Main Engine	2002-2020	16	11.5	2002 Fleet	19.5	0.0%
Underway				2010	18.6	3.1%
				2020	18.1	5.7%
		75%RO:25%MDO				
Auxiliary Engine	2002-2020	11		2002 Fleet	14.5	0.0%
All Modes				2010	13.9	4.1%
				2020	13.3	8.3%
b) Scenario B – Lower NOx emission limit of commercial technology - assumed to start in 2012						
Engine	New Engine			Forecast Fleet Average		
	Year	NOx (g/kWh)		Year	NOx (g/kWh)	Reduction from 2002
		RO	MDO			
Main Engine	2002-2011	16	11.5	2002 Fleet	19.5	0.0%
Underway	2012-2020	12	9	2010	18.6	3.1%
				2020	16.8	12.5%
		75%RO:25%MDO				
Auxiliary Engine	2002-2011	11		2002 Fleet	14.5	0.0%
All Modes	2012-2020	8.4		2010	13.9	4.1%
				2020	12.5	13.8%

5.3.2 Forecast SOx Emission Factors

SOx emissions from vessels using marine diesel oil procured in Canada will be reduced by the implementation of a 500 ppm sulphur content limit starting in 2007. The sulphur content of residual oils purchased in Canada or marine diesel oil purchased on the international market has been assumed not to be affected by this change in Canadian fuel regulations or changes in fuel sulphur limits in other jurisdictions over the period to 2020.

Estimates of the effects of lowering the maximum sulphur content of marine diesel oil in Canada to 500 ppm were developed for each type of vessel included in the inventory based on the following assumptions:

- The proportion of domestic and internationally sourced fuel remains constant at the levels estimated in Section 2.2.1;
- The sulphur content of domestic and internationally source residual oils remains the same as assumed for the base year; and
- The average sulphur content of marine diesel oil purchased in Canada decreases to 300 ppm in 2007 and remains at this level in 2010 and 2020, relative to the regulatory limit of 500 ppm (This choice for in-use sulphur content is guided by the observation that the national average sulphur content of diesel fuel for onroad vehicles is currently about 300 ppm, while the regulatory sulphur content limit for this fuel is 500 ppm.).

Lowering of the sulphur content of domestic marine diesel oil has a minor affect on the SOx emission factors except for vessels procuring all or most of their fuels from ports in North America, as evident in the factors summarized in Table 5-6. The SOx emission factors for the main engines of large ocean-going vessels are insensitive to changes in the sulphur content of marine diesel fuel because they are assumed to use 100% residual oil.

5.3.3 Forecast PM Emission Factors

Reducing the sulphur content of domestic marine diesel oil to comply with a 500 ppm limit starting in 2007 will reduce the formation and emissions of sulphate particulate matter for vessels bunkering all or most of their diesel oil from North American ports. In parallel with the results for SOx shown in Table 5-6, lowering of the sulphur content of domestic marine diesel oil is expected to reduce particulate matter emissions from merchant ferries, ocean tugs and military vessels.

The Port of Los Angeles has estimated that lowering the sulphur content of marine diesel oil from 0.2% (2000 ppm) to 500 ppm would decrease particulate matter emissions by 8% (POLA, 2005). However, this reduction is estimated by assuming a certain level of conversion of sulphur to particulate matter and has not been verified by testing.

Merchant ferries, ocean tugs and military vessel emitted a total of 77.2 tonnes of TPM, PM_{10} and $PM_{2.5}$ in 2002 (see Table 3-3), with the predominant source being ferries. This amounts to less than 1% of the particulate matter from all vessel classes. Reducing the sulphur content of the marine diesel oil burned by these vessels would reduce the baseline particulate matter emissions by approximately 8%, or 6 tonnes/year. The reduction of particulate matter emissions from lowering of the sulphur content of domestic marine diesel oil will therefore have a negligible effect on total emissions in the study area, but could result in more significant emission reductions along major ferry routes.

Table 5-6 Ratio of 2010 and 2020 SOx Emission Factors to the SOx Emission Factors in the 2002 Base Year

Vessel Class	INNAV Code	Percent Fuel Source		SOx Emission Factor Ratio (Emission Factor in 2010 or 2020/Emission Factor in 2002)		
		Domestic	International	Main Engine		Auxiliary Engine
				Underway	Manoeuvring	All Modes
Merchant (Dry)	MM	0	100	1	1	1
Merchant (Tanker)	TT	25	75	1	1	1
Merchant Auto	MA	10	90	1	1	1
Merchant Bulk	MB	20	80	1	1	1
Merchant Chemical	TL	5	95	1	1	1
Merchant Coastal	MS	45	55	1	1	1
Merchant Container	MC	5	95	1	1	1
Merchant Crude	TC	20	80	1	1	1
Merchant Ferry	MF	100	0	0.14	0.13	0.14
Merchant Gasoline	TG	0	100	1	1	1
Merchant General	MG	10	90	1	1	1
Merchant Liquified Gas	TQ	40	60	1	1	1
Merchant Molasses	TM	0	100	1	1	1
Merchant Ore	MO	20	80	1	1	1
Merchant Ore/Bulk/Oil	TO	5	95	1	1	1
Merchant Passenger	MP	55	45	1	1	1
Merchant Reefer	MR	0	100	1	1	1
Merchant RO/RO	MH	10	90	1	1	1
Merchant Super Tanker	TS	0	100	1	1	1
Merchant ULCC	TU	0	100	1	1	1
Merchant VLCC	TV	0	100	1	1	1
Tugs Ocean	HO	80	20	0.82	0.81	0.82
Warship - General	WR	100	0	0.12	0.12	0.12
Warship Surface	WS	100	0	0.12	0.12	0.12

5.4 BASELINE EMISSION FORECAST RESULTS

5.4.1 Overall Emission Trends

The forecast emissions for 2010 and 2020 are summarized in Table 5-7 assuming Scenario A for the fleet adjustments to NOx emissions and the estimated effects on SOx emissions of the 500 ppm limit on the sulphur content of marine diesel oil sold in Canada (starting in 2007). Tables 5-8 and 5-9 summarize the emissions forecast for 2010 and 2020 by type of marine vessel.

Table 5-7 Baseline Forecast of Total Emissions

Substance	Emissions				
	2002	2010		2020	
	(tonnes/year)	(tonnes/year)	% Increase	(tonnes/year)	% Increase
CO_2	3,298,991.8	3,696,368.7	12.0%	4,167,118.0	26.3%
NOx	93,699.5	102,334.5	9.2%	112,209.6	19.8%
SO_2	47,459.0	53,576.4	12.9%	61,143.3	28.8%
VOC	2,843.2	3,210.0	12.9%	3,644.2	28.2%
HC	2,843.2	3,210.0	12.9%	3,644.2	28.2%
CO	3,092.9	3,432.1	11.0%	3,834.5	24.0%
TPM	10,348.4	11,729.0	13.3%	13,362.4	29.1%
PM_{10}	8,157.0	9,241.0	13.3%	10,523.5	29.0%
$PM_{2.5}$	6,854.8	7,761.8	13.2%	8,834.9	28.9%

Table 5-8 Emission Forecast by Vessel Class and Substance – 2010

Vessel Class	Annual Emissions (tonnes/year)								
	CO_2	SO_2	NOx	VOC	HC	CO	TPM	PM_{10}	$PM_{2.5}$
Merchant (Dry)	165.6	2.8	4.9	0.2	0.2	0.1	0.6	0.5	0.4
Merchant (Tanker)	514,406.0	7,640.7	14,212.3	451.6	451.6	465.6	1,671.0	1,317.5	1,108.3
Merchant Auto	14,071.9	228.4	412.0	13.3	13.3	11.7	50.3	39.5	32.9
Merchant Bulk	1,105,802.1	17,107.9	31,888.0	1,024.9	1,024.9	941.1	3,856.9	3,028.1	2,533.5
Merchant Chemical	75,072.2	1,218.7	2,103.8	67.2	67.2	66.6	249.8	196.7	165.1
Merchant Coastal	2,162.0	29.7	61.0	1.9	1.9	1.9	7.3	5.7	4.8
Merchant Container	907,657.1	14,979.1	26,429.7	848.9	848.9	760.5	3,214.2	2,521.3	2,107.2
Merchant Crude	142,931.0	2,199.3	4,076.2	130.2	130.2	123.6	489.2	384.5	322.2
Merchant Ferry	233,089.7	35.0	4,447.6	86.0	86.0	389.6	71.2	71.2	71.2
Merchant Gasoline	1,488.3	24.8	42.4	1.4	1.4	1.3	5.1	4.0	3.4
Merchant General	245,493.4	3,950.3	7,054.5	225.9	225.9	209.9	850.8	668.2	559.4
Merchant Liquefied Gas	641.6	8.8	17.2	0.5	0.5	0.6	2.0	1.6	1.3
Merchant Molasses	883.2	14.6	24.5	0.8	0.8	0.8	2.9	2.3	1.9
Merchant Ore	48,433.0	754.2	1,416.5	45.6	45.6	40.3	172.8	135.5	113.2
Merchant Ore/Bulk/Oil	22,951.1	363.4	606.7	19.1	19.1	22.0	69.2	54.8	46.4
Merchant Passenger	205,108.8	2,498.2	4,939.0	151.7	151.7	218.4	523.0	419.3	360.2
Merchant Reefer	8,013.0	134.6	232.7	7.5	7.5	6.7	28.2	22.2	18.5
Merchant RO/RO	110,817.4	1,728.3	2,960.2	93.3	93.3	104.9	340.0	269.0	227.4
Merchant Super Tanker	8,343.0	138.3	235.0	7.5	7.5	7.4	28.0	22.0	18.5
Merchant ULCC	1,960.9	32.2	53.9	1.7	1.7	1.8	6.3	5.0	4.2
Merchant VLCC	25,251.3	415.9	700.3	22.3	22.3	22.7	82.6	65.1	54.7
Tugs Ocean	21,330.4	71.2	407.8	8.3	8.3	34.3	6.5	6.5	6.5
Warship - General	81.8	0.0	2.4	0.1	0.1	0.1	0.3	0.2	0.2
Warship Surface	213.9	0.0	6.1	0.2	0.2	0.2	0.7	0.6	0.5
All Vessels	3,696,368.7	53,576.4	102,334.5	3,210.0	3,210.0	3,432.1	11,729.0	9,241.0	7,761.8

Table 5-9 Emission Forecast by Vessel Class and Substance – 2020

Vessel Class	Annual Emissions (tonnes/year)								
	CO_2	SO_2	NOx	VOC	HC	CO	TPM	PM_{10}	$PM_{2.5}$
Merchant (Dry)	176.0	3.0	5.0	0.2	0.2	0.1	0.6	0.5	0.4
Merchant (Tanker)	543,800.7	8,077.4	14,559.8	477.4	477.4	492.2	1,766.5	1,392.7	1,171.7
Merchant Auto	14,683.7	238.3	416.7	13.9	13.9	12.2	52.5	41.2	34.4
Merchant Bulk	1,175,537.4	18,186.8	32,850.5	1,089.5	1,089.5	1,000.4	4,100.2	3,219.1	2,693.3
Merchant Chemical	80,738.0	1,310.6	2,192.6	72.3	72.3	71.7	268.7	211.5	177.6
Merchant Coastal	2,355.1	32.3	64.4	2.1	2.1	2.1	7.9	6.2	5.2
Merchant Container	1,224,281.7	20,204.4	34,546.9	1,145.0	1,145.0	1,025.8	4,335.4	3,400.8	2,842.3
Merchant Crude	149,673.0	2,303.0	4,136.4	136.4	136.4	129.4	512.2	402.6	337.4
Merchant Ferry	233,089.7	35.0	4,218.4	86.0	86.0	389.6	71.2	71.2	71.2
Merchant Gasoline	1,573.3	26.2	43.4	1.4	1.4	1.4	5.4	4.2	3.5
Merchant General	267,412.5	4,303.0	7,446.7	246.1	246.1	228.7	926.8	727.9	609.3
Merchant Liquefied Gas	679.4	9.3	17.7	0.6	0.6	0.6	2.1	1.7	1.4
Merchant Molasses	933.7	15.4	25.1	0.8	0.8	0.8	3.1	2.4	2.0
Merchant Ore	51,831.9	807.1	1,469.0	48.8	48.8	43.1	184.9	145.0	121.1
Merchant Ore/Bulk/Oil	24,033.7	380.6	615.6	20.0	20.0	23.0	72.4	57.4	48.6
Merchant Passenger	205,108.8	2,498.2	4,786.2	151.7	151.7	218.4	523.0	419.3	360.2
Merchant Reefer	9,256.4	155.5	260.5	8.6	8.6	7.8	32.6	25.6	21.4
Merchant RO/RO	119,180.9	1,858.7	3,085.1	100.4	100.4	112.8	365.7	289.3	244.5
Merchant Super Tanker	8,736.5	144.9	238.4	7.9	7.9	7.7	29.3	23.1	19.4
Merchant ULCC	2,053.4	33.7	54.7	1.8	1.8	1.9	6.6	5.2	4.4
Merchant VLCC	26,442.4	435.6	710.6	23.4	23.4	23.8	86.5	68.1	57.3
Tugs Ocean	25,244.2	84.2	457.7	9.8	9.8	40.5	7.7	7.7	7.7
Warship - General	81.8	0.0	2.3	0.1	0.1	0.1	0.3	0.2	0.2
Warship Surface	213.9	0.0	5.9	0.2	0.2	0.2	0.7	0.6	0.5
All Vessels	4,167,118.0	61,143.3	112,209.6	3,644.2	3,644.2	3,834.5	13,362.4	10,523.5	8,834.9

5.5 Emissions with Implementation of Sulphur Emission Control Area

5.5.1 Effect of Lower Fuel Sulphur Contents on SOx and Particulate Matter Emission Factors

Emissions were estimated assuming implementation of a Sulphur Emission Control Area extending over the whole study area. In this case, it was assumed that all heavy fuel oil used in the study area would have a sulphur content of 1.5% and that the marine diesel oil would have a sulphur content unchanged from the baseline forecast. The forecast changes in NOx emissions and the proportion of heavy fuel oil and marine diesel oil used in auxiliary engines were assumed to remain the same as baseline forecast.

The sulphur contents of fuels used for the SECA forecast are summarized in Table 5-10. The SOx emission factors were calculated using these assumed sulphur contents and the same fuel source weighting factors applied for the baseline forecast.

Table 5-10 Sulphur Contents Used for SECA Emission Forecast

Mode	Ocean-Going Vessels		Military Vessels	Ferry & Tug Vessels
	International Fuels	Domestic Fuels	Domestic Fuels	Domestic Fuels
	(%)	(%)	(%)	(%)
Underway				
Composite SSD & MSD	1.50	1.50	0.03	0.03
Manoeuvring				
Composite SSD & MSD	1.50	1.50	0.03	0.03
Auxiliary Engines				
All modes - Medium speed	1.40	1.10	0.03	0.03

Reduction in the sulphur content of heavy fuel oils will reduce emissions of particulate matter (as sulphate) as well as SOx. Entec (2005) estimated an 18% reduction in particulate matter would be associated with reducing the sulphur content of fuel oil from 2.7% to 1.5%. This assumption was also applied in this study by assuming the particulate matter reduction is equal to 40% of the reduction in SOx emissions, which yields an 18% reduction in PM when the sulphur content decreases from 2.7% to 1.5%.

The reduction in SOx emissions for some vessels is the same as, or similar to, that assumed in the baseline forecast. With implementation of a SECA, SOx and PM emissions from ferries will be unchanged from the baseline forecast because the sulphur content of the fuel is already below 1.5%. A fraction of tugs were assumed to be using higher sulphur fuels and the reduction in SOx and PM emissions from these vessels is therefore slightly higher than assumed for the baseline forecast. Table 5-11 summarizies the SOx and PM reductions relative to the 2002 baseline and indicates, which reductions are solely from implementing a SECA and which where are either included unchanged from the baseline forecast or a combination of the two effects.

Table 5-11 SECA Assumptions for Percent Reduction in SOx and Particulate Matter Emission Factors Relative to the 2002 Baseline

INNAV Code	Vessel Class	SOx Reduction (%)	PM Reduction (%)	Notes
MM	Merchant (Dry)	44	18	SECA effects only
TT	Merchant (Tanker)	39	16	SECA effects only
MA	Merchant Auto	42	17	SECA effects only
MB	Merchant Bulk	40	16	SECA effects only
TL	Merchant Chemical	43	17	SECA effects only
MS	Merchant Coastal	33	13	SECA effects only
MC	Merchant Container	43	17	SECA effects only
TC	Merchant Crude	40	16	SECA effects only
MF	Merchant Ferry	86	0	Same as baseline forecast
TG	Merchant Gasoline	44	18	SECA effects only
MG	Merchant General	42	17	SECA effects only
TQ	Merchant Liquified Gas	35	14	SECA effects only
TM	Merchant Molasses	44	18	SECA effects only
MO	Merchant Ore	40	16	SECA effects only
TO	Merchant Ore/Bulk/Oil	43	17	SECA effects only
MP	Merchant Passenger	30	12	SECA effects only
MR	Merchant Reefer	44	18	SECA effects only
MH	Merchant RO/RO	42	17	SECA effects only
TS	Merchant Super Tanker	44	18	SECA effects only
TU	Merchant ULCC	44	18	SECA effects only
TV	Merchant VLCC	44	18	SECA effects only
HO	Tugs, Ocean	52	0	SECA effects plus baseline forecast
WR	Warship - General	88	0	Same as baseline forecast
WS	Warship Surface	88	0	Same as baseline forecast

5.5.2 SECA Emission Forecast

Emissions with implementation of a SECA are summarized in Tables 5-12 through 5-14.

Table 5-12 Forecast Total Emissions with Implementation of a SECA

Substance	Emissions				
	2002	2010		2020	
	(tonnes/year)	(tonnes/year)	% Change	(tonnes/year)	% Change
CO_2	3,298,991.8	3,696,368.7	12.0%	4,167,118.0	26.3%
NOx	93,699.5	102,284.4	9.2%	112,209.6	19.8%
SO_2	47,459.0	31,842.1	-32.9%	36,214.6	-23.7%
VOC	2,843.2	3,210.0	12.9%	3,644.2	28.2%
HC	2,843.2	3,210.0	12.9%	3,644.2	28.2%
CO	3,092.9	3,432.1	11.0%	3,834.5	24.0%
TPM	10,348.4	9,835.3	-5.0%	11,194.9	8.2%
PM_{10}	8,157.0	7,752.0	-5.0%	8,819.6	8.1%
$PM_{2.5}$	6,854.8	6,513.6	-5.0%	7,406.9	8.1%

Table 5-13 Emission Forecast by Vessel Class and Substance with Implementation of a SECA – 2010

Vessel Class	Annual Emissions (tonnes/year)								
	CO_2	SO_2	NOx	VOC	HC	CO	TPM	PM_{10}	$PM_{2.5}$
Merchant (Dry)	165.6	1.6	4.9	0.2	0.2	0.1	0.5	0.4	0.3
Merchant (Tanker)	514,406.0	4,660.9	14,212.3	451.6	451.6	465.6	1,403.7	1,106.7	931.0
Merchant Auto	14,071.9	132.5	412.0	13.3	13.3	11.7	41.8	32.7	27.3
Merchant Bulk	1,105,802.1	10,264.7	31,888.0	1,024.9	1,024.9	941.1	3,239.8	2,543.6	2,128.1
Merchant Chemical	75,072.2	694.6	2,103.8	67.2	67.2	66.6	207.4	163.2	137.1
Merchant Coastal	2,162.0	19.9	61.0	1.9	1.9	1.9	6.3	5.0	4.2
Merchant Container	907,657.1	8,538.1	26,429.7	848.9	848.9	760.5	2,667.8	2,092.7	1,749.0
Merchant Crude	142,931.0	1,319.6	4,076.2	130.2	130.2	123.6	410.9	323.0	270.6
Merchant Ferry	233,089.7	35.0	4,447.6	86.0	86.0	389.6	71.2	71.2	71.2
Merchant Gasoline	1,488.3	13.9	42.4	1.4	1.4	1.3	4.2	3.3	2.7
Merchant General	245,493.4	2,291.2	7,054.5	225.9	225.9	209.9	706.2	554.6	464.3
Merchant Liquefied Gas	641.6	5.7	17.2	0.5	0.5	0.6	1.7	1.4	1.1
Merchant Molasses	883.2	8.2	24.5	0.8	0.8	0.8	2.4	1.9	1.6
Merchant Ore	48,433.0	452.5	1,416.5	45.6	45.6	40.3	145.1	113.8	95.1
Merchant Ore/Bulk/Oil	22,951.1	207.1	606.7	19.1	19.1	22.0	57.4	45.5	38.5
Merchant Passenger	205,108.8	1,748.8	4,939.0	151.7	151.7	218.4	460.3	369.0	317.0
Merchant Reefer	8,013.0	75.4	232.7	7.5	7.5	6.7	23.2	18.2	15.2
Merchant RO/RO	110,817.4	1,002.4	2,960.2	93.3	93.3	104.9	282.2	223.3	188.7
Merchant Super Tanker	8,343.0	77.5	235.0	7.5	7.5	7.4	22.9	18.1	15.2
Merchant ULCC	1,960.9	18.0	53.9	1.7	1.7	1.8	5.2	4.1	3.4
Merchant VLCC	25,251.3	232.9	700.3	22.3	22.3	22.7	67.7	53.4	44.9
Tugs Ocean	21,330.4	41.7	407.8	8.3	8.3	34.3	6.5	6.5	6.5
Warship - General	81.8	0.0	2.4	0.1	0.1	0.1	0.3	0.2	0.2
Warship Surface	213.9	0.0	6.1	0.2	0.2	0.2	0.7	0.6	0.5
All Vessels	3,696,368.7	31,842.1	102,334.5	3,210.0	3,210.0	3,432.1	9,835.3	7,752.0	6,513.6

Table 5-14 Emission Forecast by Vessel Class and Substance with Implementation of a SECA – 2020

Vessel Class	Annual Emissions (tonnes/year)								
	CO_2	SO_2	NOx	VOC	HC	CO	TPM	PM_{10}	$PM_{2.5}$
Merchant (Dry)	176.0	1.7	5.0	0.2	0.2	0.1	0.5	0.4	0.3
Merchant (Tanker)	543,800.7	4,927.2	14,559.8	477.4	477.4	492.2	1,483.9	1,169.9	984.2
Merchant Auto	14,683.7	138.2	416.7	13.9	13.9	12.2	43.6	34.2	28.5
Merchant Bulk	1,175,537.4	10,912.1	32,850.5	1,089.5	1,089.5	1,000.4	3,444.1	2,704.0	2,262.3
Merchant Chemical	80,738.0	747.1	2,192.6	72.3	72.3	71.7	223.0	175.6	147.4
Merchant Coastal	2,355.1	21.6	64.4	2.1	2.1	2.1	6.9	5.4	4.5
Merchant Container	1,224,281.7	11,516.5	34,546.9	1,145.0	1,145.0	1,025.8	3,598.4	2,822.7	2,359.1
Merchant Crude	149,673.0	1,381.8	4,136.4	136.4	136.4	129.4	430.3	338.2	283.4
Merchant Ferry	233,089.7	35.0	4,218.4	86.0	86.0	389.6	71.2	71.2	71.2
Merchant Gasoline	1,573.3	14.7	43.4	1.4	1.4	1.4	4.4	3.5	2.9
Merchant General	267,412.5	2,495.7	7,446.7	246.1	246.1	228.7	769.3	604.2	505.8
Merchant Liquefied Gas	679.4	6.0	17.7	0.6	0.6	0.6	1.8	1.4	1.2
Merchant Molasses	933.7	8.6	25.1	0.8	0.8	0.8	2.5	2.0	1.7
Merchant Ore	51,831.9	484.3	1,469.0	48.8	48.8	43.1	155.3	121.8	101.7
Merchant Ore/Bulk/Oil	24,033.7	216.9	615.6	20.0	20.0	23.0	60.1	47.6	40.3
Merchant Passenger	205,108.8	1,748.8	4,786.2	151.7	151.7	218.4	460.3	369.0	317.0
Merchant Reefer	9,256.4	87.1	260.5	8.6	8.6	7.8	26.7	21.0	17.5
Merchant RO/RO	119,180.9	1,078.1	3,085.1	100.4	100.4	112.8	303.5	240.2	203.0
Merchant Super Tanker	8,736.5	81.1	238.4	7.9	7.9	7.7	24.0	18.9	15.9
Merchant ULCC	2,053.4	18.9	54.7	1.8	1.8	1.9	5.4	4.3	3.6
Merchant VLCC	26,442.4	243.9	710.6	23.4	23.4	23.8	70.9	55.9	47.0
Tugs Ocean	25,244.2	49.3	457.7	9.8	9.8	40.5	7.7	7.7	7.7
Warship - General	81.8	0.0	2.3	0.1	0.1	0.1	0.3	0.2	0.2
Warship Surface	213.9	0.0	5.9	0.2	0.2	0.2	0.7	0.6	0.5
All Vessels	4,167,118.0	36,214.6	112,209.6	3,644.2	3,644.2	3,834.5	11,194.9	8,819.6	7,406.9

6. SPATIAL GRIDDING OF EMISSIONS

6.1 GENERAL METHOD

The general methodology for spatial gridding of the marine emission inventory is based on regional vessel routing. Emissions are allocated to a 4 km x 4 km grid cell within a region based on the observed frequency of vessel traffic. Historic vessel traffic routes are used to develop a spatial percentage factor for a specific grid cell within a region. These spatial proration factors are multiplied by the regional monthly emission estimates produced by the Marine Emission Inventory Tool. The results are written to a text file in a suitable format for input into Environment Canada's air quality models. This approach is described in detail in subsequent sections.

6.2 DEVELOPMENT OF SPATIAL PRORATION FILES

Shipping lanes are taken from ongoing work at the University of Delaware using historic data on empirically reported ship positions. A recent dissertation by Dr. Chengfeng Wang in Dr. Corbett's research program developed a model called the Waterway Network Ship Traffic, Energy and Environment Model (STEEM) for characterizing ship traffic, estimating energy use, and assessing the environmental impacts of shipping. Separately from this work, Dr. Corbett and Dr. Wang have applied STEEM to geographically characterize energy use and emissions for inter-port ship movement for North America, including the United States, Canada, and Mexico (Wang, Corbett and Firestone, 2006).

6.2.1 Description of STEEM

STEEM was developed to quantify and geographically represent inter-port vessel traffic and emissions as contrasted with in-port activities which have been well-characterized in other studies (U.S. EPA, 1999a,b; Starcrest Consulting Group, 2002, 2003 & 2004), and in this regard is a complement to the Marine Inventory Tool applied for this project. By applying advanced GIS tools and using better data sets, STEEM adopts some of the strengths of both top-down and bottom-up approaches and attempts to overcome the weaknesses in each approach. First, the model builds an empirical waterway network based on shipping routes revealed from 20-year observed historical ship locations. The spatial allocation is more accurate than a bottom-up approach, which uses speculative routes, and than a top-down approach, which uses biased spatial proxies. Second, as in a bottom-up approach, this model estimates energy use and emissions using complete historical ship movements, ship attributes, and the distances of routes. The calculations are expected to be more accurate than a top-down approach, which relies on the statistics of the world fleet and its operating profiles. Third, the automation of repetitive processes makes this method capable of producing global energy and emissions inventories, which is a daunting task with existing bottom-up approaches. Fourth, since the network can be updated, modified, re-used, and shared among users, STEEM is perhaps more cost-effective than both the top-down and the bottom-up approaches. In fact, the application of this model to produce prorated traffic intensities is perhaps the first reuse of the spatial network.

6.2.2 Prorating Emission Inventory Results

A strength of the empirical waterway network built in STEEM is that it not only aligns the shipping lanes with actual shipping activity, but also defines the relationships among routes, segments and nodes with ArcGIS Network Analyst tools. In the empirical waterway network, intersections of shipping lanes and ports are defined as nodes, and shipping lanes between two immediate

nodes are defined as segments. Traffic can flow in and out of segments only through nodes. A route is defined as an actual non-stop path ships take between one origin and one destination port. By combining these strengths, the marine inventory can be allocated spatially.

Levelton provided Drs. Corbett and Wang a set of region boundaries corresponding to the scope of work for this project. The geographic regions are described in detail in Section 1.3. Polygons were defined in ArcGIS for each of these regions, and emissions results from STEEM were compared to emissions results from the Levelton Marine Inventory Tool. For parity, underway vessel activity was compared. A strength of the Levelton work is that the traffic data used to estimate vessel activity and emissions for the Canadian side of the Great Lakes, St. Lawrence Seaway, and Eastern Canada is obtained from INNAV. This ship activity data appears to include more vessel movements than Canadian data currently used by Drs. Corbett and Wang in STEEM. As expected, total emissions estimated by Levelton were greater than emissions estimated by STEEM, a result of the more complete INNAV data describing vessel movements. Another possible explanation for differences perhaps include more detailed activity assumptions by Levelton for near-shore, since the current modelling of STEEM to produce North American emissions estimates necessarily included common inputs to describe vessel speed and power reductions within 20 km of port; these assumptions would likely be modified and/or applied with greater detail by Levelton during this project.

Based on this joint review, Levelton and Drs. Corbett and Wang recognized that the empirical waterway in STEEM described similar patterns of activity to the Levelton work, and that the Marine Emission Inventory Tool may describe more completely the emissions totals for vessel activity in INNAV. Drs. Corbett and Wang then processed their emissions inventory within the Levelton polygons from STEEM-estimated values to percentages of total estimates, enabling Levelton to spatially allocate the estimated underway emissions to empirical shipping lanes.

Wtihin ArcGIS, the STEEM emissions inventory for each emission region was summed. For each region, grid cells in the spatially resolved emissions inventory in STEEM were then divided by the total emissions in the region to produce an intermediate raster file. Intermediate raster files were then multiplied by 100 to produce a raster file with the value of each grid cell as the percentage of total emissions of each Levelton region. This process used ArcGIS tools, as illustrated in Figure 6-1.

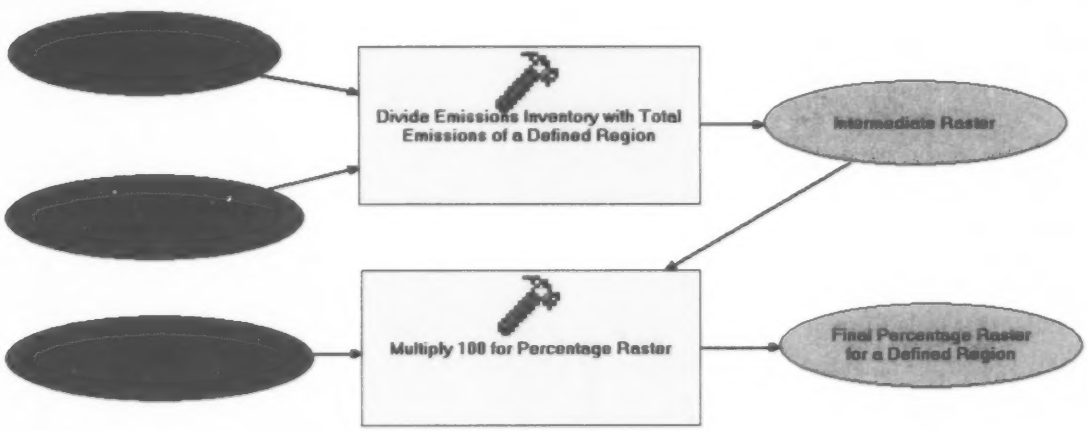
Divide Emissions Inventory with Total Emissions of a Defined Region
Intermediate Raster
Multiply 100 for Percentage Raster
Final Percentage Raster for a Defined Region

Figure 6-1 ArcGIS Calculations to Produce Prorated Percent Emissions from the Empirical Network in STEEM.

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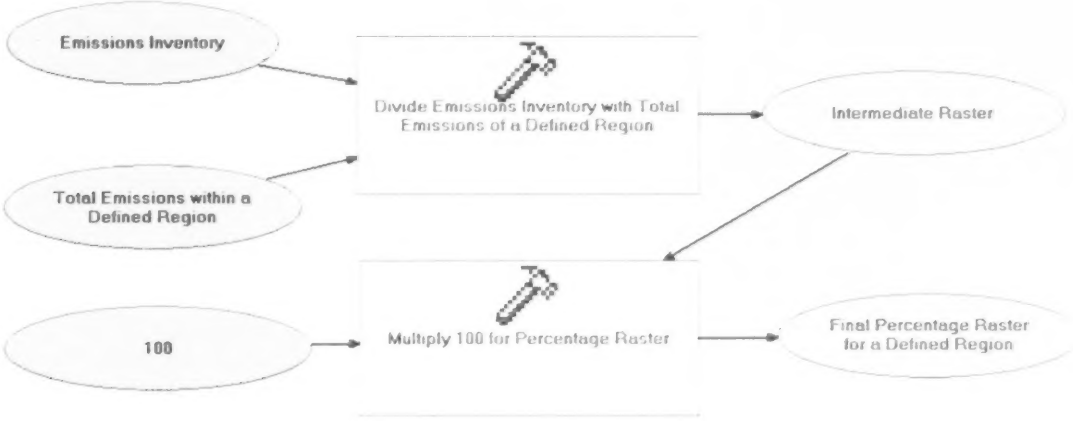
Emissions Inventory
Divide Emissions Inventory with Total Emissions of a Defined Region
Intermediate Raster
Total Emissions within a Defined Region
100
Multiply 100 for Percentage Raster
Final Percentage Raster for a Defined Region

Figure 6-1 ArcGIS Calculations to Produce Prorated Percent Emissions from the Empirical Network in STEEM.

6.2.3 Limitations and Opportunities for Improvement

Overall, the technique is robust and prorated files provided to Levelton may be reused with the Marine Emission Inventory Tool. There are some inherent limitations in this prorated approach to spatially allocate results from the marine emission inventory. These limitations reveal potential for approaches similar to the one used in this project to become more accurate and descriptive.

First and most obvious, ship activity included in INNAV but not described in STEEM could be using shipping lanes and route segments different than those assigned in STEEM. We believe that the empirical waterway network built on 20-year observed ship locations likely reveals most of the major shipping routes, and that the patterns in STEEM were generally similar to those in the Levelton model. While this suggests that most of the shipping lanes are represented in the Network, ship activity in the Marine Emission Inventory Tool may occur on these routes with different intensity than estimated by STEEM; this could produce within-region biases that could be overcome by directly modelling the INNAV movements and Marine Emission Inventory Tool activity inputs in the empirical network.

Second, vessel activity described in the Levelton Marine Inventory Tool may include many small movements across short distances and/or near ports. These activities were not typically in the Canadian data provided for STEEM, and may represent additional unique waterway paths that ships in the INNAV data are using. This would mean that the prorated network could assign these movements inaccurately to shipping routes and segments revealed in the current network. As discussed by Wang, Corbett, and Firestone (2006), the empirical shipping network can be refined in confined regions and nearer to port to describe these more local movements. However, some coding may be required to allow the major ship activity to conform to the primary routes, and enable these minor routing assignments only for appropriate movements.

Third, some shipping lanes within a region may be used (or usable) primarily during certain months or seasons. This could result from winter conditions, for example, especially in the emission regions of the Great Lakes. Such conditions would suggest that monthly prorated files could better reveal the seasonality of shipping activity. Alternatively, the INNAV data and Levelton input parameters could be directly modelled within STEEM using the current and/or regionally modified empirical routes.

6.3 Method of Generating Gridded Emissions Using the Marine Inventory Tool

Additional functionality was added to the Marine Inventory Tool for generating gridded inventory output files in a format suitable for modelling purposes. The spatial proration files described in Section 6.2 were provided by the University of Delaware in ASCII format and are read in as input files by the Marine Emission Inventory Tool. The application reads the spatial percentage factor for each grid cell and multiplies this value by the monthly emission total for the pollutant in the region. The results are written to an ASCII output file in a format suitable for modelling. The file format is identical to the modelling format the SECA Team has adopted for the North American marine inventory. A separate file is generated for each inventoried pollutant, by month, and by region. This information is stored in the header of each file as well as in the file name. An example for NOx emissions in Region 5 for the month of January 2002 is as follows:

File name: region5_NOx_January_output.txt

File header:

Region: 5
Substance: NOx
Month: January

Year:	2002
ncols	176
nrows	75
xllcorner	9980.9777211627
yllcorner	5171.6116977276
cellsize	4
NODATA_value	-9999

The remaining values in the file (not shown) are the emission totals in metric tonnes in each 4 km x 4 km grid cell. For organizational purposes, the output files are written to separate directories under the main C:\marine directory for the 2002 baseline, 2010 forecast, and 2020 forecast. Continuing with the above example, the directory structure is:

C:\marine\gridding\region5_baseline_output\
C:\marine\gridding\region5_2010_output\
C:\marine\gridding\region5_2020_output\

The gridding process is initiated from the Report Menu in the Marine Inventory Tool, as shown in Figure 6-2. The user has the option of running the gridding routine for the baseline inventory or the forecasts. The gridding routine should be initiated when the baseline inventory and forecasts have been generated in previous processing steps.

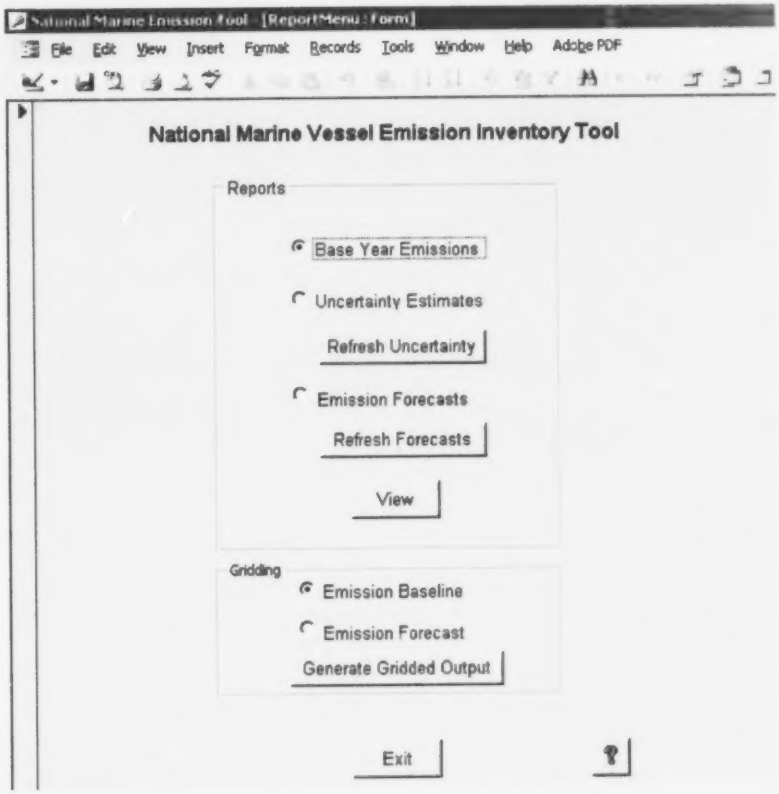

Figure 6-2 Report Menu with Gridding Options

6.4 GRIDDED RESULTS

A large number of output files in a format suitable for air quality modelling were generated by the gridding routine and they have been provided electronically as a separate deliverable. The maximum number of output files generated is as follows:

No. of grid files = 9 pollutants x 16 regions x 12 months x 5 scenarios (base, 2010, 2020, SECA 2010, SECA 2020) = 8,640 files (9)

The actual number of files produced is less than the maximum because some regions had no reported vessel movements during winter months.

Figure 6-3 illustrates the shipping lanes underlying the calculation of the percentage of emissions in each grid cell in each of the emission regions. Note that the colour coding varies for shipping lanes by region due to the distribution ranges that are selected by the GIS software The percent ranges defined by the colours are indicated in Table 6-1.

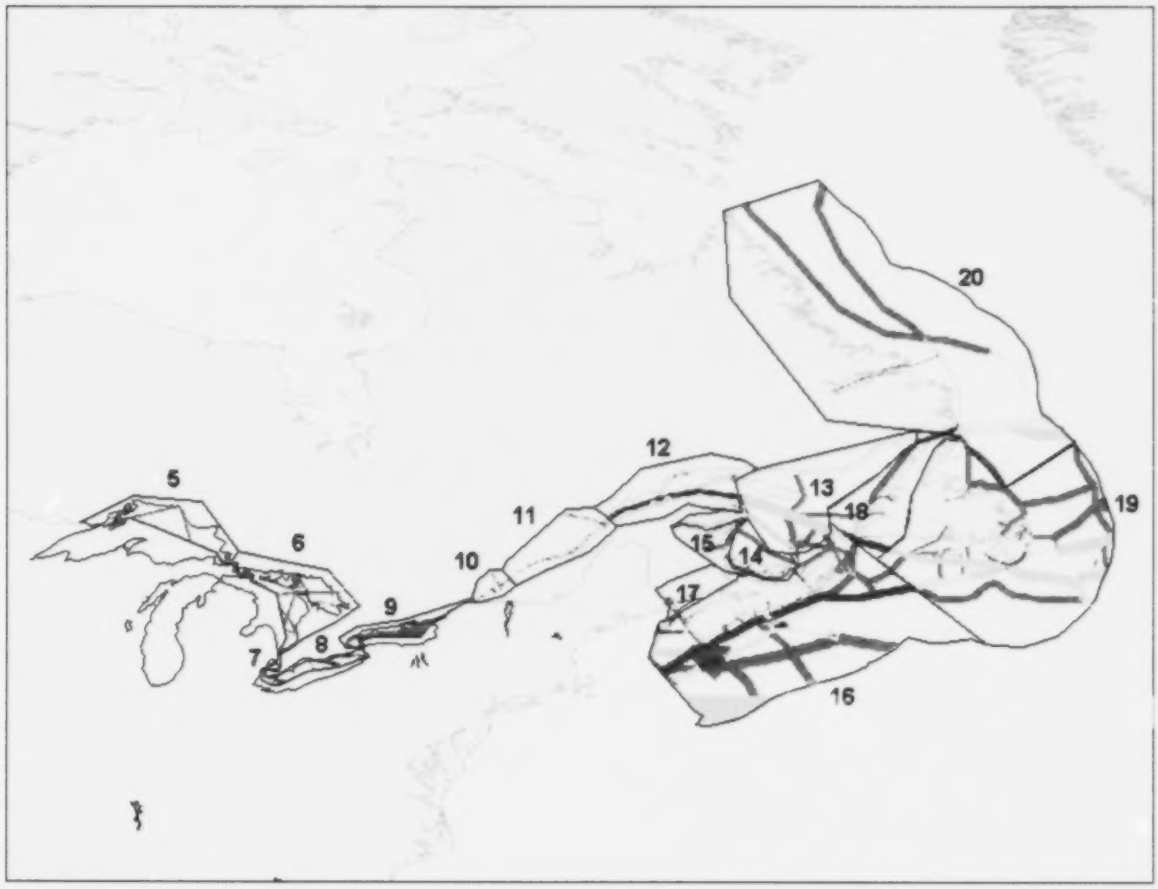

Figure 6-3 Study Area Regions and Empirical Shipping Lanes

Table 6-1 Legend for Colours in Figure 6-3

Region	Percent of Emissions in Region			
5	0.01% - 0.2%	0.21% - 0.5%	0.51% - 2.0%	2.01% - 3.17%
6	0.01% - 0.2%	0.21% - 0.5%	0.51% - 1.0%	1.01% - 1.69%
7	0.01% - 0.2%	0.21% - 0.5%	0.51% - 3.0%	3.01% - 6.47%
8	0.01% - 0.2%	0.21% - 0.5%	0.51% - 1.0%	1.01% - 1.81%
9	0.01% - 0.2%	0.21% - 0.5%	0.51% - 1.0%	1.01% - 2.15%
10	0.01% - 0.2%	0.21% - 0.5%	0.51% - 2.0%	2.01% - 5.41%
11	0.01% - 0.2%	0.21% - 0.5%	0.51% - 0.8%	0.81% - 1.36%
12	0.01% - 0.02%	0.02% - 0.05%	0.06% - 0.1%	0.11% - 0.19%
13	0.01% - 0.02%	0.02% - 0.05%	0.06% - 0.1%	0.11% - 0.39%
14	0.01% - 0.2%	0.21% - 0.5%	0.51% - 1.0%	1.01% - 2.51%
15	0.01% - 0.2%	0.21% - 0.5%	0.51% - 0.8%	0.81% - 1.17%
16	0.1% - 0.3%	0.4% - 0.6%	0.7% - 1.4%	1.5% - 27.8%
17	0.01% - 0.03%	0.04% - 0.06%	0.07% - 0.14%	0.15% - 2.80%
18	0.1% - 2.0%	2.1% - 5.0%	5.1% - 10.0%	10.1% - 32.7%
19	0.01% - 0.01%	0.02% - 0.03%	0.04% - 0.05%	0.06% - 0.12%
20	0.01% - 0.01%	0.02% - 0.02%	0.03% - 0.07%	0.08% - 0.20%

7. CONCLUSIONS

- The activity-based emission inventory developed in this project reflects the current state-of-knowledge of the emission characteristics and power output of main and auxiliary engines used on commercial marine vessels while underway and in port on Canadian waters.
- Data from the Canadian Coast Guard's INNAV system that was used in the emission inventory to estimate movements of individual commercial vessels in 2002 provides an accurate basis for estimating emissions by class of vessel and for resolving these emissions temporally and spatially within the study area.
- Emissions from commercial marine vessels are forecast to increase 9% to 13% by 2010 and 20% to 29% by 2020, as compared to the 2002 base year. Bulk carrier, container and tanker vessels are the three largest contributors to emissions of carbon dioxide and the primary pollutants of concern in regard to effects on air quality. The combined contribution from this group of vessels ranges from 67% to 74% of total emissions.
- By 2010, the IMO NOx emission limit implemented starting in 2000 will reduce the fleet-average NOx emission factors for ocean-going vessels by 3.1% for main engines, and by 5.7% for auxiliary engines, at an estimated 2% engine/vessel replacement rate. By 2020, the fleet-average NOx emission factor will decrease by 4.1% for main engines and 8.3% for auxiliary engines.
- From the analysis of the emissions by month, emissions are lowest in January through March and remain near their highest levels in May, July, August, September and October. The months when minimum or maximum values occur are not the same for all pollutants.
- The implementation of a Sulphur Emission Control Area (SECA) in the study area to limit the sulphur content of marine fuels to not more than 1.5% is forecast to decrease annual SOx emissions 33% by 2010, and 24% by 2020, relative to emissions in 2002. By reducing the formation of sulphate from combustion of sulphur in marine fuels, a SECA will also significantly reduce the growth in annual PM_{10} and $PM_{2.5}$ emissions from 13% to -5% by 2010, and from 29% to 8% by 2020.

8. RECOMMENDATIONS

The following recommendations focus cn further work that would lead to improvements in the marine emission inventory tool, the baseline emission inventory and the SECA emission forecast.

Marine Emission Inventory Tool:

1) Modify the program module and database used to calculate emissions with assumed growth and emission control scenarios so that a single version of the Marine Emission Inventory Tool can generate, store, report and delete results for a number of emission analysis scenarios.

2) Develop an interface to link the emission results and INNAV ship movements to a geographical information system (GIS) software and enable mapping of emissions by ship movement and enhanced spatial analysis of ship activities and emissions.

Baseline Emission Inventory and Forecast:

1) Conduct a survey of ocean-going ships arriving at the busiest ports in the study area to improve statistics on the following parameters and use the results of the survey to improve the assumptions and factors used in the Marine Emission Inventory Tool:

   - Type and power rating of main engines.
   - Type and power rating of auxiliary engines.
   - Quality and sulphur content of main engine and auxiliary engine fuel used while underway, manoeuvring and at dock.
   - Load factors for main engine and auxiliary engines while manoeuvring and at dock.
   - Underway and manoeuvring vessel speeds.
   - Duration of operation of auxiliary engines per port call.
   - Percent of ship's main and auxiliary engines that are in compliance with the IMO NOx emission limits.

2) Conduct measurements, in accordance with ISO protocols, of NOx, PM_{10} and $PM_{2.5}$ emissions while vessels are underway and at dock for the major classes of marine vessels in the emission inventory. Utilize field test data to calculate specific emission factors in grams/kWh. This would expand the very limited or absent measurement data now available for estimation of engine emission factors for these pollutants and also ensure that the emission factors used in the Marine Emission Inventory Tool reflect the current vessel fleet.

3) Update the growth forecast for cargo transported by ocean-going vessels, preferably stratified by type of marine vessel using the INNAV vessel types, and with separate consideration of regions in the study area that may have different growth prospects. These updated growth factors should then be used to update the growth factors in the Marine Emission Inventory Tool.

SECA Forecast:

1) Investigate the effect on SOx and particulate emissions of implementing 0.1% and 0.2% sulphur content limits for fuels burned by auxiliary engines of ocean-going vessels while in port.

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